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Reef Life Survey: Establishing the ecological basis for conservation of shallow marine life

Graham J. Edgar[a,b,*], Antonia Cooper[a,b], Susan C. Baker[c], William Barker[d], Neville S. Barrett[a], Mikel A. Becerro[e], Amanda E. Bates[f], Danny Brock[g], Daniela M. Ceccarelli[h], Ella Clausius[a,b], Marlene Davey[b], Tom R. Davis[i], Paul B. Day[j], Andrew Green[k], Samuel R. Griffiths[l], Jamie Hicks[g], Iván A. Hinojosa[m,n], Ben K. Jones[o], Stuart Kininmonth[p,q], Meryl F. Larkin[r,s], Natali Lazzari[e], Jonathan S. Lefcheck[t], Scott D. Ling[a], Peter Mooney[b], Elizabeth Oh[a], Alejandro Pérez-Matus[u], Jacqueline B. Pocklington[v], Rodrigo Riera[m], Jose A. Sanabria-Fernandez[e], Yanir Seroussi[w], Ian Shaw[x], Derek Shields[b], Joe Shields[a], Margo Smith[s], German A. Soler[a], Jemina Stuart-Smith[a], John Turnbull[y], Rick D. Stuart-Smith[a,b]

[a] *Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania 7001, Australia*
[b] *Reef Life Survey Foundation, 60 Napoleon St, Battery Point, Tasmania 7000, Australia*
[c] *School of Natural Sciences, University of Tasmania, Hobart, Tasmania 7001, Australia*
[d] *Nature Coast Marine Group, 20 Trunketabella Street, Potato Point, NSW 2545, Australia*
[e] *The BITES Lab, Center for Advanced Studies of Blanes (CEAB-CSIC), Acc Cala S Francesc 14, 17300 Blanes, Gerona, Spain*
[f] *Department of Ocean Sciences, Memorial University of Newfoundland, St. John's, NL A1C 5S7, Canada*
[g] *Department for Environment and Water, 81-95 Waymouth Street, Adelaide, South Australia 5000, Australia*
[h] *ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia*
[i] *Fisheries Research, NSW Department of Primary Industries, PO Box 4321, Coffs Harbour, NSW 2450, Australia*
[j] *Carijoa – Marine Environmental Consulting, 29 Sydenham Street, Rivervale, Perth, WA 6103, Australia*
[k] *Nature Coast Marine Group, 10 Garden Street, Geelong, Victoria, Australia*
[l] *Exto En Vism, P.O. Box 113, Dodges Ferry, Tasmania 7173, Australia*
[m] *Departamento de Ecología, Facultad de Ciencias y Centro de Investigación en Biodiversidad y Ambientes Sustentables (CIBAS), Universidad Católica de la Santísima Concepción, Chile*
[n] *Millennium Nucleus for Ecology and Sustainable Management of Oceanic Islands (ESMOI), Departamento de Biología Marina, Universidad Católica del Norte, Coquimbo, Chile*
[o] *School of Natural Sciences, Edith Cowan University, Joondalup, WA 6027, Australia*
[p] *School of Marine Studies, The University of the South Pacific, Suva, Fiji*
[q] *Heron Island Research Station, University of Queensland, St Lucia, QLD, Australia*
[r] *National Marine Science Centre, Southern Cross University, Bay Drive, Coffs Harbour, NSW 2456, Australia*
[s] *Combined Hunter Underwater Group, 106 Northcott Drive, Adamstown Heights, NSW 2289, Australia*
[t] *Tennenbaum Marine Observatories Network, Smithsonian Environmental Research Center, Edgewater, MD, USA*
[u] *Subtidal Ecology laboratory, Estación Costera de Investigaciones Marinas, Departamento de Ecología, Facultad de Ciencias Biológicas, Pontificia Universidad Católica de Chile, Casilla 114-D, Santiago, Chile*
[v] *Science and Management Effectiveness Branch, Parks Victoria, Melbourne, Victoria 3000, Australia*
[w] *Underwater Research Group of Queensland, 24 Pulle St, Yeerongpilly, QLD 4105, Australia*
[x] *Solitary Islands Underwater Research Group, PO Box 4096, Coffs Harbour, NSW 2450, Australia*
[y] *School of Biological, Earth and Environmental Sciences, University of NSW, Kensington 2033, Australia*

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ABSTRACT

Reef Life Survey (RLS) provides a new model for ecological monitoring through training experienced recreational divers in underwater visual census methods to the level of skilled scientists. Detail produced is similar to that of programs with professional scientific teams, at low cost to allow global coverage. RLS differs from most other

* Corresponding author at: Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania 7001, Australia.
E-mail address: g.edgar@utas.edu.au (G.J. Edgar).

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Effects of fishing
Marine protected area
Sea snake

citizen science initiatives in its emphasis on rigorous training and data quality rather than open participation, selectively involving the most skilled and committed members. Volunteers participate primarily because they appreciate the close relationship with scientists, other divers, and managers, and see their efforts directly contributing to improved environmental outcomes. RLS works closely with Australian management agencies, scheduling annual events at core monitoring sites associated with 10 inshore marine protected areas Australia-wide. Surveys of 12 offshore Australian Marine Parks (AMPs) are realized through 2–4 week voyages in a sailing catamaran crewed by volunteers. Across the AMP network, RLS surveys have quantified densities of fishes, mobile invertebrates, macroalgae and corals at 350 shallow coral reef sites (180 sites surveyed on two or more occasions), providing an understanding of (i) population changes amongst threatened species including sea snakes, (ii) responses of fish and invertebrate populations following fisheries closures, (iii) ecosystem-wide impacts of marine heat-waves, and (iv) the extent that AMPs spanning the network comprehensively encompass national coral reef biodiversity. This scientist/volunteer/manager collaboration could be greatly expanded globally (presently 3537 sites in 53 countries).

1. Background

Environmental managers are struggling in the face of accelerating impacts on biological diversity in the “Anthropocene”, which marks the sixth major extinction crisis on Earth (e.g. Dirzo et al., 2014; Kidwell, 2015). Managers urgently need better knowledge and effective tools to minimize declining populations of native species – a consequence of cumulative threats, including climate change, habitat loss, over-harvesting, pollution and invasive non-native species (Dulvy et al., 2003; Edgar et al., 2005; Pimm et al., 2014). Unlike an oil spill or bushfire, many serious threats remain poorly recognised because they progress imperceptibly, eroding natural values over time-scales of decades to centuries (the ‘shifting baseline syndrome’, Dayton et al., 1998). Such chronic impacts are prevalent in the marine realm, where ecological change occurs out-of-sight below the sea surface, and little quantitative baseline data and capacity for ongoing monitoring exist.

The major challenge to collecting ecological data on marine systems is cost. Fieldwork requires weather-dependent access to remote sites using boats and other specialized equipment. Consequently, most research funding for marine environmental monitoring supports remote-sensing or large offshore vessels. In Australia, the majority of government funding for marine field research supports two ‘blue-water’ research vessels, one directed at Antarctic research. Research effort is thereby concentrated within large, technically sophisticated teams operating within a narrow footprint (the boat track), while most of Australia’s 8.2 million km^2 exclusive economic zone remains unexplored.

At the other funding extreme are university researchers, who typically work at local scales on targeted questions. Since 1992, our University of Tasmania research team has advanced long-term continental-scale research through underwater surveys of fishes, large invertebrates and macroalgae, inside and outside marine protected areas (MPAs) across southern Australia (Edgar and Barrett, 2012). However, given locally idiosyncratic ecological changes in 12 MPAs monitored, we ultimately realized that a generalized understanding of MPA success required long-term data from tens to hundreds of MPAs, which was beyond logistical capabilities for a single university research team.

To overcome this challenge, we explored whether volunteer divers could expand the spatial scale of our marine biodiversity data collection. Initial trials had mixed results (Barrett et al., 2002); we found some divers to be enthusiastic, highly skilled, and capable of producing rigorous scientific data with little training. Others did not achieve basic competencies, while the majority were intermediate, producing noisy data of potential value, but requiring considerable curation. Ongoing efforts were directed towards the most competent divers, a relatively small proportion (10–20%) of the total. Here we detail subsequent progress in developing and applying a new citizen science model that selectively involves the most skilled volunteers. We then outline major achievements including collaborative assistance to Parks Australia and other Australian environmental management agencies.

2. Reef Life Survey

2.1. Origins

Reef Life Survey (RLS) was initiated as a three-year pilot program (2007–10) supported by the Australian government through the Commonwealth Environment Research Facilities program and hosted by the University of Tasmania. The program aimed to test the capacity of a team of volunteer divers to collect standardized density data on marine life across the broadest geographic, temporal and taxonomic scales, which a single team of professional scientists is unable to cover. We had five goals:

1. To design and apply a standardized methodology for censusing shallow marine life from the tropics to the poles.
2. To identify, train and support a community of citizen scientists comprising the most capable recreational divers in the application of visual survey methods.
3. To collate, curate and freely distribute data online.
4. To develop regular communication pathways between scientists, volunteer divers, and managers, all committed to improving marine conservation outcomes.
5. To communicate marine environmental knowledge to the wider public.

The first challenge faced was that a large cohort of volunteer divers could not be registered for university diving without substantial costs for diving qualifications and annual re-certification. The initial solution was to conduct RLS activities under the umbrella of an established environmental not-for-profit, People and Parks Foundation (see: http://www.peopleandparks.org/). Reef Life Survey Foundation was subsequently registered independently as an environmental charity with tax-deductible status in December 2012, with divers as members, and activities run as a large organised dive-club. RLS activities have subsequently been led by the RLS Foundation with close links to the University of Tasmania, who have provided data management, analysis and some administrative support.

To solve a second challenge – engagement of management agencies and the recreational diving sector – an Advisory Committee was formed with representatives from national, state, and territory environment departments, and diving groups. Advisory Committee meetings occur at 2–3 month intervals, covering survey planning and recent findings, public communication, governance, finances and safety.

2.2. Methods

2.2.1. General protocols

Each RLS survey involves three distinct searches centred along a 50-m transect line, for: (i) fishes, (ii) mobile invertebrates and cryptic fishes, and (iii) sessile organisms such as corals and macroalgae (Fig. 1). Full details of the standardized methods are available online (Reef Life

Survey Foundation, 2019a). Methods are adapted from those developed for scientific surveys of reef communities conducted across the eastern tropical Pacific (ETP, Edgar et al., 2011), including off all major islands within the Galapagos Marine Reserve (Edgar et al., 2004a), and ecological surveys across southern Australian waters through the Australian Temperate Reef Collaboration (ATRC; https://atrc.org.au/). Methods for ETP, ATRC and RLS are identical for fishes and mobile invertebrates other than the number and spatial distribution of replicates, consequently combined analyses can capitalize on extensive ATRC time-series dating back to 1992.

Benthic communities of macroalgae, corals and other sessile invertebrates are scored in situ by ETP and ATRC divers whereas they are recorded using photo-quadrats by RLS divers, and later scored by specialists. Training RLS divers in species-level macroalgal and coral taxonomic skills was not considered feasible in terms of required capacity, dive time constraints, and the additional effort needed to generate enthusiasm amongst volunteers for learning further species identification. Expert identification skills are critical for success in RLS where, much like amateur bird watchers, RLS divers are those who are highly motivated to learn species of fish and mobile invertebrates. Fewer recreational divers have this same motivation for macroalgae and coral, thus specialist scientists digitize these components.

Two transects are usually surveyed at each site, generally parallel at different depths depending on local topography. Sites and depths are chosen with the aim of maximising the range of reef habitat types covered within each location. Diving constraints including decompression schedules and air consumption generally limit depths to shallower than 20 m, but surveys have been conducted to 32 m using nitrox gas mixes and 42 m using closed circuit rebreather. Underwater visibility, depth, and compass direction are recorded at the time of each survey.

Four complementary approaches are used for RLS field operations:

1. Trained divers undertake surveys on their own initiative, including regular surveys of their local reefs and opportunistic surveys while on holidays (9% of species records in RLS database).
2. RLS Foundation schedules annual surveys at core monitoring locations distributed around Australia, where divers gather as a group to resurvey long-term monitoring sites. To minimize job disruption, these surveys generally extend over four days, centred on a weekend; however, longer periods are scheduled at remote locations, to a maximum of two weeks. RLS Foundation covers diving and accommodation costs through grants and local support, while volunteers cover their travel-related expenses (46% of records).
3. Sites are surveyed from a sailing catamaran over 2–4 week periods under direction of a volunteer skipper (generally DS or GJE), allowing access to remote offshore sites, including Pacific and Caribbean crossings, and circumnavigation around Australia (27% of records).
4. Academic researchers, and staff of management agencies, conduct scientific surveys using the RLS methodology (18% of records). Collaborating organizations include the Smithsonian Institute's Marine Global Earth Observatory program, who apply RLS methods at long-term reef monitoring sites across north and central America; Spain's National Research Council (CSIC), who have coordinated surveys at 350 sites around Spain, Portugal and north Africa, with resurvey currently underway; and Memorial University Newfoundland, who have established a network of sites along Canada's east coast. New collaborations with local universities and institutions in Chile are expected to operate similarly, including with ESMOI, Universidad Católica del Norte (Coquimbo), Pontificia Universidad Católica de Chile (Santiago), and Universidad Católica de la Santísima Concepción.

2.2.2. Method 1: fish surveys

The species identity, estimated abundance, and size-category of all fishes sighted within 5×50 m^2 blocks either side of the transect line are recorded on waterproof paper as divers swim slowly beside the line. The two transect blocks include independent counts that are averaged to characterize the transect, hence can include the same individual fish if it crosses the transect and is within a diver's search field on both blocks. Mammals, sea snakes, turtles, cephalopods and other large free-swimming animals are also recorded. Size categories used are 25, 50, 75, 100, 125, 150, 200, 250, 300, 350, 400, 500, 625 mm; and 125 mm increments above 625 mm. Divers take photographs of unrecognised species for later confirmation of identities using field guides and advice from appropriate taxonomic experts. Occasionally, when no photograph is available and for species without distinctive morphological characters (e.g. juvenile parrotfishes), taxa are recorded to the highest taxonomic

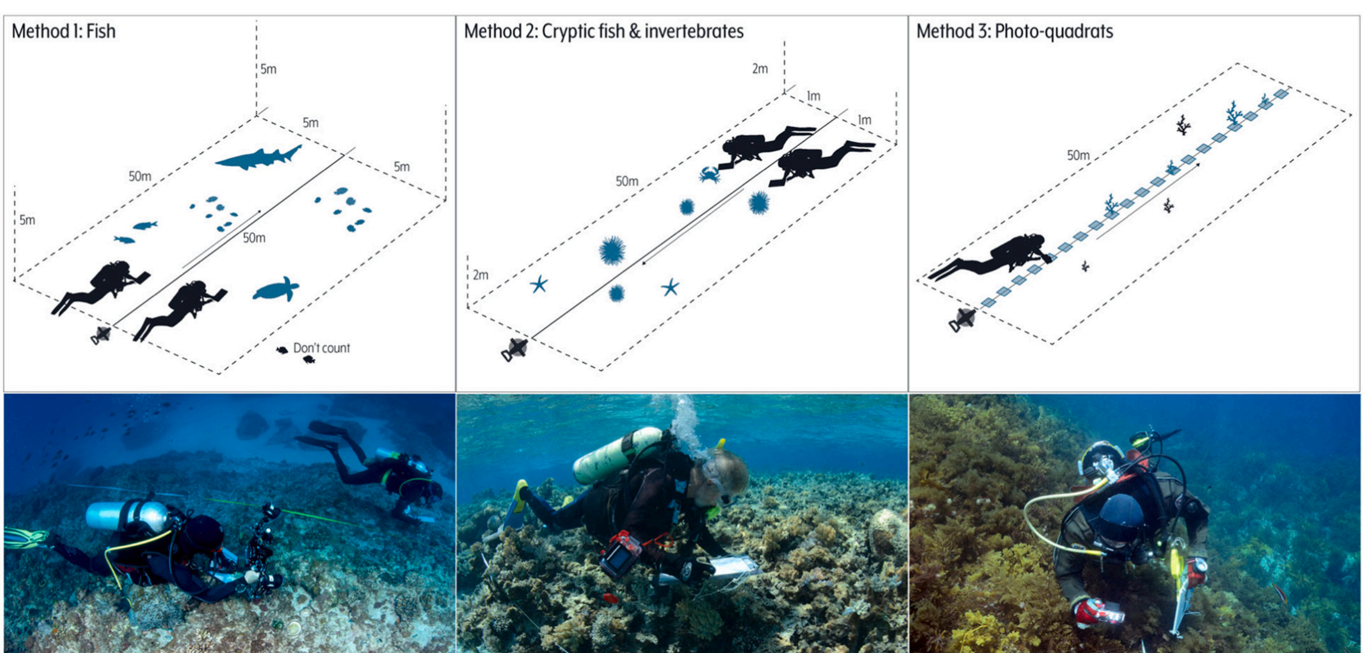

Fig. 1. Diagrammatic depiction of survey methods.

resolution for which there is confidence. Species observed outside the survey blocks, or during laying of the transect, are recorded as 'Method 0'. Such records represent a presence record, useful for producing distributional maps, but are not used in quantitative analyses.

2.2.3. Method 2: macroinvertebrate and cryptic fish surveys

Large mobile macroinvertebrates (echinoderms, molluscs and crustaceans >25 mm) and cryptic fishes are surveyed along the same transect lines set for fish surveys. Divers swim near the seabed, recording animals sighted within 1 m of each side of the line. This requires searching along crevices and undercuts, but without moving rocks. Cryptic fishes are closely associated with the seabed and are often overlooked during Method 1 surveys. Predominant amongst cryptic fish families are gobies, blennies, triplefins, eels, groupers, squirrelfishes, sweepers and scorpionfishes (for full list of families, see Edgar et al., 2017b). Cryptic fishes are placed in the same size categories as for Method 1.

2.2.4. Method 3: photo-quadrats of benthic cover

The cover of sessile invertebrates and macroalgae is estimated along each 50 m line using digital photo-quadrats of the seabed (mean area ~ 0.4 × 0.3 m) every 2.5 m (20 in total). Later, the percentage cover of different macroalgal, coral, sponge and other attached invertebrate taxa are obtained by trained scientists scoring functional groups present under 100 points per transect (5 points per image). Percentage cover of benthic flora and fauna in photo-quadrats was scored using Coral Point Count initially (Kohler and Gill, 2006); more recently, Squidle+ (see: https://squidle.org/), an online annotation tool that allows point-based scoring of seabed imagery, has been used. For routine photo-quadrat processing, functional groups comprise a set of 50 categories aligned with the 'Collaborative and Annotation Tools for Analysis of Marine Imagery and Video' (CATAMI) benthic imagery classification scheme (Althaus et al., 2015).

2.2.5. Data quality

Although the accuracy of citizen science data is sometimes queried by professional scientists, RLS volunteer data were indistinguishable from professional data in a quantitative continental-scale assessment of temperate reefs for all metrics investigated: species richness, total density, mean fish size, and species composition (Edgar and Stuart-Smith, 2009). Variation between individual divers within volunteer and professional groups also contributed little to total estimated variance between transects. Few would query the best amateur bird watchers' ability to accurately identify bird species (Horns et al., 2018) and RLS marine naturalists are comparably skilled, each spending hundreds of hours consulting identification guides. Many RLS volunteers are marine ecology students; most are scientifically qualified (44% have completed postgraduate studies, and 74% a bachelor's degree).

Data standards are achieved and maintained through screening of interested divers (who need >50 dives of open water experience completed before participating, but most have many more), 1:1 training of volunteers by qualified trainers over at least eight survey dives, data-quality benchmarks to complete training, regular dialogue between divers and researchers in the field, checks of divers' images by scientific experts, use of an online tool ('Frequency Explorer'; see: https://reeflifesurvey.com/frequency-explorer/) that generates a species inventory with images ranked by abundance for any selected set of sites worldwide (and includes automated flashcards for testing divers' knowledge of those species), and screening of data for common errors during data-entry sessions.

2.2.6. Data management and quality control

Volunteers enter survey data into region-specific Microsoft Excel templates with built-in cell lookups for species and site names to minimize spelling errors and out of range records. These are forwarded to the University of Tasmania data management team after quality checks by local coordinators. Manual and automated database checks prevent upload until all errors are corrected, including out of range species, implausible size or abundance, taxonomic errors, and metadata mismatches between divers surveying the same site. Error correction includes an error reporting form available for images and locations of species sightings on the RLS website field guide (*Reef Species of the World*, see 2.3.9 below). Data processing forms part of the National Reef Monitoring Network, a sub-facility within the Integrated Marine Observing System (IMOS; see: http://imos.org.au/). Following IMOS database redevelopment currently underway, all global RLS data will be available from within the same portal as a wealth of other marine environmental datasets.

2.2.7. Data limitations, error and bias

All ecological survey methods applied by marine researchers (e.g., grabs, trawls, baited videos, seabed photos, drone monitoring, satellite images, eDNA) involve trade-offs in the geographic extent of surveys (span), site detail (grain), frequency, and taxonomic resolution. No one size fits all.

The RLS underwater visual census methodology is designed to answer broad-scale questions within the range of environmental conditions for which visual methods can be safely applied – shallow, non-turbid locations with minimal diving hazards. RLS methods are thus not generally appropriate for water depths below safe diving limits (30 m for SCUBA, mesophotic depths for rebreather), pelagic habitats, turbid water (<4 m underwater visibility), and locations with hazards such as crocodiles. They are also inefficient in soft-sediment habitats where few animals are sighted.

As with all methods, visual census techniques detect some species more efficiently than others, affecting density estimates (Edgar et al., 2004b). Introduced bias includes variation between observers, differences in species detection (Bernard et al., 2013), and over-counting of highly mobile animals (Ward-Paige et al., 2010). Statistical methods can account for some of these biases, including by relating observer identifiers to response data and by partitioning the relative influences of multiple explanatory factors (Bird et al., 2014).

A key advantage of the RLS protocol is that it collects twice as much information with relatively little extra dive time by encompassing two conjoint blocks rather than one. Fish densities do, however, tend to be lower along transect lines already set due to exodus of timid fish (Emslie et al., 2018); regardless, numbers when assessed in initial trials at 13 Lord Howe Island sites were not greatly reduced on return counts (total fish density per 250 m transect block ± SE: 244 ± 32 while laying line vs 229 ± 26 SE for subsequent return blocks). Total fish species richness was higher across two conjoint return transect blocks (23.6 ± 2.0) but lower on a single return block (16.3 ± 1.4) than for a single block surveyed while laying out the line (20.5 ± 2.3). Thus, lower counts occur with some fishes frightened away during transect deployment, but the number of 'missed' species is more than compensated by duplicated blocks. Overall, we consider departure of fishes to be one of many biases associated with counts – the important issue is that such biases are consistent from time to time, and site to site, so that data can be compared in a relative sense. Timid species which disappear as the line is laid out, but for which occurrence and size data are considered valuable (e.g. exploited species), are recorded as an 'off-transect record (method 0)' to indicate their presence at the time and place of the survey.

For RLS data, observer error is small relative to site-to-site variation (Edgar and Stuart-Smith, 2009). Detection biases in counts of different species can, however, be large, with divers under-estimating some species below 10% of absolute densities (Edgar et al., 2004b). Regardless, we regard most biases as systematic, affecting estimates of absolute numbers but not relative densities between locations or times, which can therefore be directly compared (see Edgar et al., 2004b, where species counts were compared before and after removal of kelp canopy). However, this assumption should be considered when interpreting results, and may not always hold, for example, where large fishes are attracted towards divers inside reserves but repelled outside (Willis et al., 2000).

A key trade-off in field surveys is between detail at individual sites and the number of sites covered (Jones et al., 2015). Our RLS sampling design maximises the amount and taxonomic breadth of information gathered at each site by a minimum of two divers, each with a single tank of air. This protocol prioritises regional coverage with up to four sites surveyed per day, but at the cost of low within-site replication. Collection of more information per site requires either additional divers in the water or changing tanks mid-survey, the latter reducing site coverage. Including gaps between multiple transects extended as a linear series, as applied in some reef census methodologies (e.g. Hodgson, 1999), does little to alleviate within-site replication limitations. For example, four 20 m transects, each separated by a 5 m gap along a depth contour, represent replicates for the 100 m total transect span at that depth (Done et al., 2017); additional extended transects are still needed to characterize a reef site extending across a range of depths.

For the Great Barrier Reef, data collected by RLS divers complement data collected through the Long Term Monitoring Program (AIMS LTMP) conducted by the Australian Institute of Marine Sciences (Emslie et al., 2020), a global best-practice in coral reef monitoring. AIMS LTMP finely resolves the long-term temporal signal in coral reef change by minimising variation in wave exposure and depth of transects to reduce spatial noise in analyses. RLS sites have little within-site replication and are surveyed less regularly, thus providing a coarser temporal signal, but allow the generality of AIMS LTMP findings to be assessed across extended wave exposure and depth regimes, and for mobile invertebrates, cryptic fishes and macro-algae in addition to corals and large fishes (Stuart-Smith et al., 2017a).

2.2.8. Diver engagement and safety

A total of 296 volunteer and professional scientists have contributed data after training in RLS methods. Many have participated long-term: 27 of the initial 115 divers (23%) trained in the first two years of the program remain actively engaged 12 years later. This longevity is attributable to personal motivation involving long term goals: to “contribute to marine science and management” (89% of 36 respondents in internal survey of RLS divers), for “further knowledge of marine life” (83% positive response), and to “contribute to conservation in general” (66% positive response). RLS divers see “knowledge sharing” (91%) as the most valuable outcome when participating in events.

No serious accidents have been reported by RLS divers in >15,000 dives. This achievement is partly due to the generally shallow diving depths surveyed (mean 7 m), with decompression illness rarely a major concern. Probably of greater importance is the minimum level of experience (>50 dives) required to participate in RLS activities, and safety recommendations of the RLS Foundation Safety Committee (Reef Life Survey Foundation, 2019b). Assessment of diver competence forms part of initial training, where divers need to be comfortable in the water for safety, to maintain focus on data collection rather than dive skills or hazards, and to minimize collision damage to sensitive habitats. Diver questionnaires indicate that only 6% have <4 years diving experience, and 45% have been diving for >10 years; 59% have logged over 500 dives.

2.3. Outcomes

2.3.1. Science

RLS is now the largest resource of standardized abundance data for marine animal species encompassing all continents, with associated photographs of most species as a confirmatory record (and online global field guide). A total of 5427 species (3361 chordates, 341 crustaceans, 1190 molluscs, 535 echinoderms) have been recorded from 3537 sites in 53 countries (Fig. 2), from Svalbard to Antarctica. Each recorded species occurs in 135 transect blocks on average. RLS data are freely accessible online through multiple portals – RLS website, the Australian Ocean Data Network, Atlas of Living Australia, and Global Biodiversity Information Facility (GBIF). Scientific users have downloaded over 500 million species records through the GBIF data portal in the past three years alone.

The RLS dataset is unique as a marine resource. Moreover, nothing equivalent exists in the terrestrial realm, which would require coincident density estimates of plants, insects, birds, reptiles and mammals. RLS data provide a basis for global macro-ecological studies (e.g. Edgar et al., 2017a), for testing theoretical ecological models (e.g. Waldock et al., 2019), and as an irreplaceable historical yardstick for improved scientific understanding of global ecological change (Stuart-Smith et al., 2017a). Over 100 scientific publications have utilized RLS data, including six published in *Nature* (Cinner et al., 2016; Edgar et al., 2014; Gill et al., 2017; Stuart-Smith et al., 2013; Stuart-Smith et al., 2018;

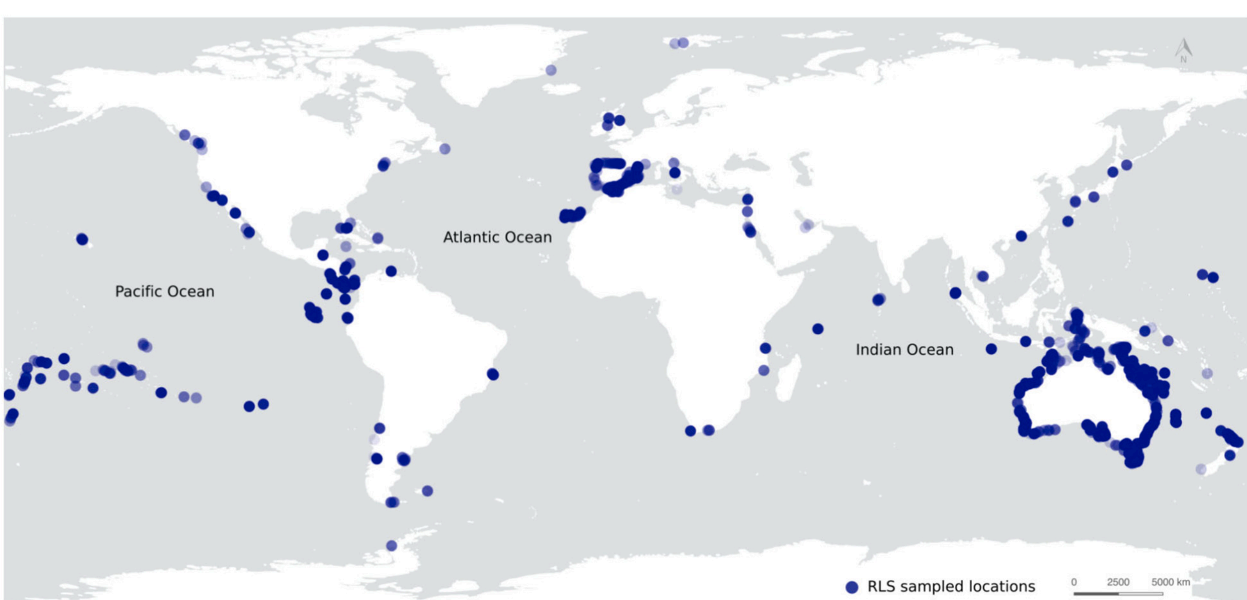

Fig. 2. Global distribution of 3537 sites surveyed by RLS divers for years 2008–2020 (blue dots; darkness of shading increases with site overlap). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Stuart-Smith et al., 2015a) and two in *Science* (Brandl et al., 2019; Cinner et al., 2020). RLS scientific collaborations are established with researchers in 18 countries.

2.3.2. Environmental planning and management

Using RLS data and associated indicators related to climate change, fishing pressure and other specific threats (Stuart-Smith et al., 2017a), planners can now more accurately assess where impacts to shallow marine life are distributed, supporting decision-making between alternative environmental planning scenarios. RLS data also contribute to predictive models describing the distribution of reef communities, an advance on planning processes that utilize habitat maps as a surrogate for ecological patterns (Thomson et al., 2014).

Marine protected area (MPA) management, in particular, has benefited from RLS analyses, which have identified design features necessary to successfully attain conservation goals, and also described realistic expectations once new MPAs are declared. The primary review document associated with planning of the Australian Marine Park (AMP) network, for example, referenced studies that utilize RLS data 31 times (Beeton et al., 2015).

MPA management insights advanced through RLS studies include:

1. Planning often biases MPA placement towards locations with few fishery or natural resources (Edgar et al., 2009), but such areas are generally low conservation priorities (Devillers et al., 2015; Edgar et al., 2008).
2. Populations of large fishes and lobsters increase in effective MPAs, whereas populations of small fishes, grazing invertebrates and primary producers show variable responses (Edgar and Stuart-Smith, 2009; Edgar et al., 2017c; Soler et al., 2015; Strain et al., 2019).
3. Ecological changes in effective MPAs progress over decades (Edgar et al., 2009).
4. Most (~90%) MPAs worldwide do not produce detectable biodiversity conservation benefits when assessed as fish biomass gain, whereas some are extremely effective (Edgar et al., 2014; Sanabria-Fernandez et al., 2019). Relative to effective no-fishing MPAs, fishing has reduced reef fish biomass by more than two-thirds worldwide (Edgar et al., 2014).
5. Conservation benefits of MPAs for reef communities increase exponentially with the accumulation of five key planning features – no-take, enforced, old (>10 years), large (>100 km^2), and isolated by deep water or sand, but the extent of benefit varies greatly between different reef fish families (Edgar et al., 2014).
6. MPAs that restrict fishing have lower conservation value than no-take marine reserves, as very little fishing pressure is needed to functionally remove large predators from reefs (Campbell et al., 2018).
7. MPAs rapidly lose effectiveness when management capacity is inadequate, or when not supported by strong socio-cultural institutions, high social engagement, and backing of communities dependent on marine resources (Cinner et al., 2016; Gill et al., 2017).
8. MPAs along heavily populated coasts have much lower fish biomass than remote reserves, but greater potential for recovery when MPAs are effectively managed (Cinner et al., 2018).
9. No-fishing MPAs provide an irreplaceable reference for understanding effects of fishing at scales ranging from target species, to bycatch, to whole of ecosystem. They therefore offer amongst the most useful fishery-independent data for guiding fisheries management, if located and planned for such purposes (Edgar et al., 2018).
10. Indicators based on species traits can be more sensitive than traditional indicators based on taxonomy in detecting ecological responses in MPAs (Coleman et al., 2015).

2.3.3. State of the environment indicators

To be interpretable, signals in multi-dimensional field-survey data need simplification to univariate metrics that summarise impacts of specific threats on ecosystems. Sensitive new RLS indicators summarise the impacts of ocean warming (the Community Temperature Index: mean temperature at centre of species range weighted by log abundance) and overfishing (B20: biomass of fishes ≥20 cm length) on reef communities (Stuart-Smith et al., 2017a). Both of these indicators have been accepted by the Biodiversity Indicators Partnership managed through the United Nations, for tracking progress towards global Sustainable Development Goals and Convention on Biological Diversity targets (https://www.bipindicators.net/). Within Australia, RLS, associated ATRC, and AIMS LTMP data provided most of the quantitative marine information included in the most recent (2016) Commonwealth State of the Environment Report (soe.environment.gov.au/themes-all). A total of 922 of 2022 RLS sites around Australia have been surveyed on more than one occasion (46% of total; Fig. 3), allowing a continental scale assessment of change.

2.3.4. Fisheries management

RLS data arguably comprise the largest fishery-independent dataset for auditing sustainability of shallow water reef fisheries worldwide. Currently, most fished species are managed with little information on the stock size or population dynamics of target and by-catch species, and catch statistics are confounded by variation in fishing effort and gear types. Major discrepancies were found between overall trends inferred from Australian stock assessment models and overall trends observed in underwater surveys, suggesting that fisheries management regimes can be unsustainable even when recognised as best-practice (Edgar et al., 2018; Edgar et al., 2019).

2.3.5. Climate change impact assessment

Analysis of RLS data highlights how the changing climate is affecting shallow marine life, including interactions with fishing. Heatwaves rapidly change fish communities, with local outcomes that can be predicted from thermal preferences of individual species and redistribution of functional groups (Day et al., 2018). Tropical coral reef ecosystems were found to be most affected by warming events in two ways: (i) by loss of coral habitat following bleaching, and (ii) by elevated temperatures directly influencing fish population growth (Stuart-Smith et al., 2018). Redistribution and homogenisation of biota were observed across the full span of the Great Barrier Reef and Australian Coral Sea Islands Territory following heatwaves, with profound ecosystem consequences due to changes in the proportional abundance of important functional groups (Stuart-Smith et al., 2018).

RLS data have also been used to predict warming-related species loss and changes in local species composition over the next century (Stuart-Smith et al., 2017b). Proximity to thermal limits is predicted to be more important than warming rates when assessing likelihood of local species extirpation (Stuart-Smith et al., 2015a; Stuart-Smith et al., 2017b). RLS data also indicate functional elements of ecosystems that provide key targets for management efforts. For example, stabilising the number of species on reefs should buffer against climate change related declines in local fish biomass independent of total animal numbers, habitat and environmental factors (Duffy et al., 2016a).

2.3.6. Pollution impact assessment

The most accurate assessment of point-source pollution impacts is achieved when historical data exist, by means of before-after-control-impact comparisons. RLS site data are densely distributed as a baseline in many regions, providing historical 'before' data in the vicinity of potential stochastic catastrophic pollution events such as oil spills (Edgar and Barrett, 2000).

In south-eastern Australia, microplastics were found to be ubiquitously present at RLS sites (Ling et al., 2017), and reef communities found to change rapidly along gradients in heavy metal pollution, local

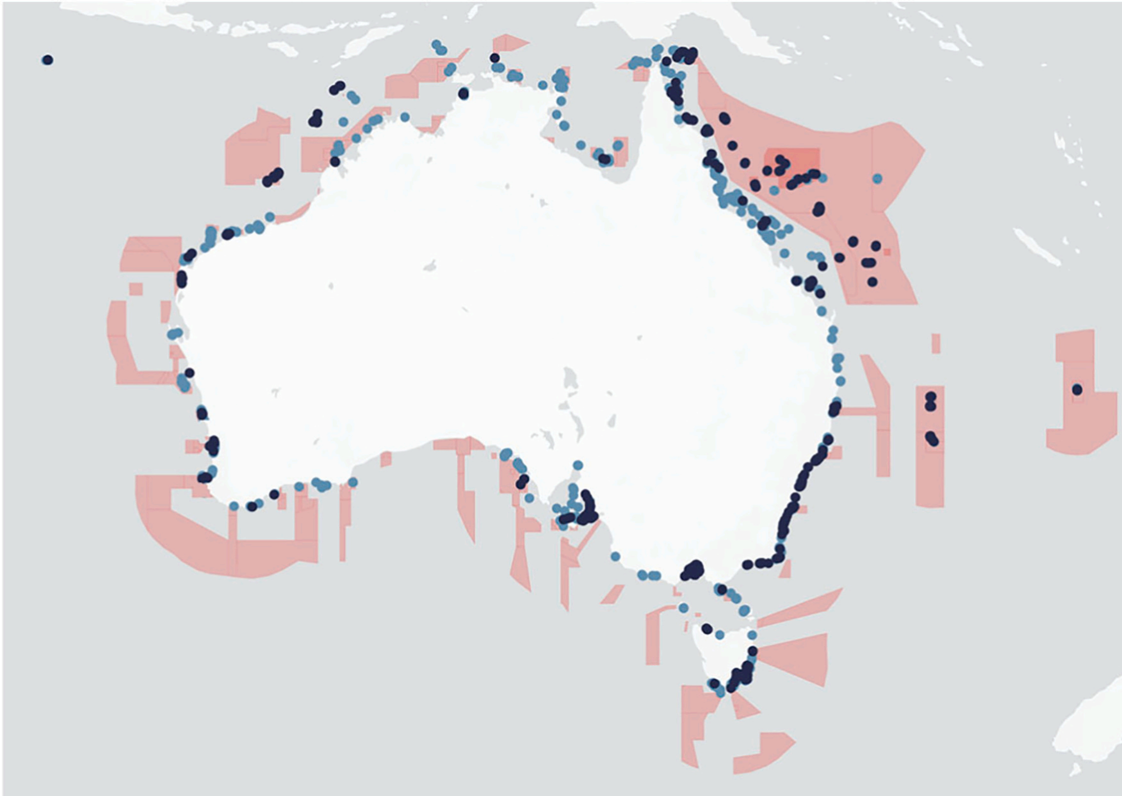

Fig. 3. Distribution of 2022 sites surveyed by RLS divers around Australia (black, sites surveyed on two or more occasions; blue, sites surveyed once). At the scale of this map, most sites are overlapping. Australian Marine Parks are shown in red. State MPAs are not highlighted as generally too small to appear at this scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

human population density, and with proximity to city ports (Stuart-Smith et al., 2015b). Densities of large slow-growing species decline along pollution gradients regardless of whether they are fishes, invertebrates or macroalgae (Fowles et al., 2018; Ling et al., 2018b).

2.3.7. Introduced pest assessment

RLS data allow the mapping of marine pest distributions at spatial scales ranging from local to global (Stuart-Smith et al., 2015b). Few reefs surveyed by RLS divers have multiple introduced species, other than in the eastern Mediterranean (where the rabbitfishes *Siganus luridus* and *Siganus rivulatus* are extremely abundant; see: https://reeflifesurvey.com/survey-data/) and in urbanised temperate estuaries (e.g. Derwent estuary, Tasmania, where introduced species predominate. Stuart-Smith et al., 2015b). By relating population trends in native species to the arrival and changing densities of invasive species, the magnitude of impacts on native species, and likely associated drivers, can be inferred.

2.3.8. Threatened species assessment

Adequate threat assessment requires long-term broad-scale data, therefore the threat status for most reef species is unknown. For hundreds of marine species, RLS data provide the only quantitative information on population trends across the species' range, including for many cryptic fishes (Edgar et al., 2017b). For example, RLS data were central to assessment of Red handfish (*Thymichthys politus*), recently listed as Critically Endangered by the International Union for Conservation of Nature (https://www.iucnredlist.org/search?taxonomies=101151&searchType=species). RLS data also improve understanding of population recovery or otherwise for species already recognised as threatened, and hence can be used to assess efficacy of management interventions aimed at species recovery.

2.3.9. Public environmental education

RLS data, blogs, maps and species identification tools are available online (see: http://reeflifesurvey.com), allowing anyone to follow survey findings shortly after they are recorded. Online products within the website include '*Reef Species of the World*' (see: https://reeflifesurvey.com/species/search.php), a locality-specific online photographic and information guide to shallow marine life of most interest to divers. Communication of findings through diverse media outlets helps generate greater community awareness of marine conservation issues, and the magnitude and consequences of ecosystem threats. The RLS website receives over 170,000 page views annually from visitors from >100 countries.

2.3.10. Science capacity building

RLS volunteers gain first-hand knowledge of living marine species. Some divers attracted to the program to assist conservation efforts have been inspired to change careers to marine environmental science. Postgraduate students from 11 Australian and 12 overseas universities have applied RLS methods. Extended field trips offer a pathway for students to experience the intricacies and splendour of marine communities underwater. This is particularly useful for university students who may otherwise be fully focused on theoretical models and desktop studies.

2.3.11. Exploration and discovery

Surveys include voyages to islands with marine fauna and flora unexplored and previously unknown. Progressing from geomorphological maps of habitats to biological ecosystems, RLS data allow the first global mapping based on abundance data of 10 marine animal classes (Edgar et al., 2017a). Undescribed species have been recorded and photographed, contributing to species descriptions by taxonomic experts (e.g. the haemulid *Plectorhinchus caeruleonothus*, Johnson and Wilmer, 2015).

2.4. Constraints

2.4.1. Funding and resources

RLS Foundation outcomes have been achieved from a very small funding base. Average annual income over the past five years has been A $200,000 (US$140,000), mostly through philanthropic support from The Ian Potter Foundation and contracts from government agencies for scientific reports and communication products (see financial statements available in annual reports: https://reeflifesurvey.com/rls-annual-reports/).

Considerable in-kind support has been provided from the University of Tasmania, the NESP (National Environmental Science Program) Marine Biodiversity Hub, the Integrated Marine Observing System, and government marine management agencies. The most valuable in-kind support has been provided by RLS volunteers, who contribute an average of 4.3 h for each transect surveyed (including gear cleaning and preparation, species identifications, data entry, photo-quadrat processing and posting), with an additional 2.2 h travel time (times derived from 36 diver questionnaire). Thus, over 87,000 h have been contributed to achieve the 13,429 RLS transects completed to date.

2.4.2. Over-reliance on key personnel

As a volunteer-operated organisation, the RLS Foundation has, until recently, relied on two key personnel (GJE and RDSS) for most administration, grant-writing and diver training, with a single University of Tasmania staff member (AC) leading fieldwork organisation, communication with divers, and accounting. This unsustainable concentration of responsibility has been reduced recently through capacity building: additional trainers, communication officer (EC), and regional leaders taking responsibility for diving activities in Western Australia (PD), South Australia (JH and DB) and New South Wales (JT and TRD). Further devolution of responsibility and increased administrative support will be needed for further expansion, particularly given increasing time requirements for accounting, permit obligations, and engaging meaningfully with Indigenous groups. Such decentralisation is important in building organisational resilience – distributing knowledge, multiplying capabilities, and creating staff backup for important roles.

2.4.3. Relationships with management agencies

Staff of Australian MPA management agencies participate in RLS Foundation Advisory Committee meetings, promote outreach, guide surveys towards priority locations within their jurisdictions, and support open distribution of data. Science/management relationships are, however, tested on rare occasions when analysis of data indicates declining environmental condition, unsuccessful management intervention, or inadequate spatial planning. While the scientific interpretation and publication of findings is separate to the RLS Foundation, whose principal role is to collect and distribute objective data, researchers participating in the RLS Foundation are prolific users of survey data in scientific publications. Consequently, the publication of 'bad news' stories can potentially affect relations with the RLS Foundation.

This issue has been well-managed to date amongst collaborating agencies participating in the RLS Foundation Advisory Committee, including through discussion of research findings prior to publication and face-to-face information sessions. Nevertheless, occasional disagreement is to be expected. The most extreme example involved an empirical test of the contention that Australian fisheries are amongst the best managed worldwide, even though catch statistics indicate a 31% mean decline in catches from 2005 to 2015 (Edgar et al., 2018). Australian fisheries agencies attribute the ongoing catch decline to past overfishing that has been countered by more precautionary management, which now leaves more fish in the sea. By contrast, analysis of RLS and ATRC data from 533 sites distributed around Australia indicated mean densities of commercially exploited species declined by ~33% over 10 years at fished locations, but increased in no-take MPAs by ~25%. Populations of unfished species showed a non-significant decline (11% in no-take MPAs, 16% in fished zones). Edgar et al. (2018) concluded that declining catches are better attributed to declining stock sizes than more precautionary management.

Within a day, this publication attracted negative reaction from: (i) the Australian Fisheries Management Authority ("AFMA rejects the claim that there have been rapid declines across Australian fish stocks"; https://www.afma.gov.au/response-research-paper-edgar-et-al-regarding-australian-fishery-stocks), (ii) the peak Australian industry body for fisheries organizations (Seafood Industry Australia), and (iii) the major funder of Australian fisheries research (Fishing Research and Development Corporation: "FRDC responds to attack on Australian fisheries science"). The debate led to a series of scientific papers (Edgar et al., 2018; Edgar et al., 2019; Gaughan et al., 2019; Little et al., 2019) and a workshop, ultimately identifying structural problems in Australian fisheries management that need to be resolved.

3. Australian Marine Parks – a case study in science, management and public collaboration

3.1. Australian Marine Parks

Offshore from coastal waters that are managed by State government authorities, the 58 Australian Marine Parks (AMPs) cover 2,762,724 km^2 of ocean surrounding Australia (https://parksaustralia.gov.au/marine/) (Fig. 3). This network expanded fivefold on 1 July 2018, when regulations associated with a complex arrangement of park management zones were enacted for 44 AMPs. This expansion raised substantial challenges for Parks Australia, the responsible management authority, in efficiently managing these new parks.

High amongst Parks Australia's priorities was the need to understand ecological values in the AMPs. Very little was known of existing biodiversity, and baseline information for evaluating the effectiveness of management was largely lacking. Such information is particularly critical for determining whether zone placement within AMP boundaries is optimal with respect to such values as threatened species and important habitats, within the overlapping footprint of potentially harmful activities.

An additional challenge is the measurement of performance, including recovery of exploited populations and important ecological functions in the face of widespread environmental degradation outside of AMP boundaries. Through the medium term, managers need to identify whether activities allowed in different zones are providing positive biodiversity outcomes, or whether changes to zoning plans or additional management actions are warranted.

Ecological monitoring provided a solution, ideally undertaken using standardized methods that allow direct comparisons with baseline and external reference sites, and between monitoring periods. However, the diversity of habitats, shallow to abyssal water depths, and sheer vastness of the area under management exceeded the capabilities of conventional monitoring programs. Monitoring all AMPs, habitats and species was not possible and thus prioritization was required.

In response to this challenge, Parks Australia collaborated with RLS Foundation to identify biodiversity values and to track ecological change on shallow coral reefs. Although coral reef habitats cover only a small proportion of the total area of AMPs, they contain a large proportion of total species, and are most highly valued by the public. AMPs are all remote and include 22 tropical and 3 subtropical marine parks, distributed across a 5500 km longitudinal and 2000 km latitudinal span from Ningaloo in the west to Norfolk Island in the east, and including Ashmore Reef (350 km off the Australian coast, 220 km from Timor) and Mellish Reef (780 km off the Australian coast, 650 km from Papua New Guinea and 780 km from the Solomon Islands).

3.2. Reef Life Survey expeditions in tropical Australian Marine Parks

Between 2012 and 2017 (i.e. prior to enactment of zone restrictions on fishing), RLS expeditions targeted all 12 Australia Marine Parks (AMPs) where shallow coral reef habitat was indicated in bathymetric charts, including all 22 reef systems in the largest AMP, the Coral Sea MP. A total of 350 coral reef sites were surveyed in AMPs, as well as a similar number of associated external reference sites. Over half of sites (55%) have since been revisited on at least one occasion, with densities of 1470 fish and invertebrate species now recorded.

These expeditions were only possible because of their cost-effectiveness. Each 2–4 week field trip involved a four-person RLS crew of skilled volunteer divers and boat skipper. Divers typically surveyed three sites per day as the vessel – a sponsored 12 m cruising catamaran – traversed an offshore route. The total cost of a typical 3-week trip was A$3000–$13,000. This compares with ~$140,000 cost for a typical dive trip involving four professional scientists for three weeks. Costs per site surveyed on professional trips are, however, reduced with additional divers and runabout vessels onboard the main vessel. Overall, for the cost of surveying 10 sites with professionally engaged biologists, over 150 sites have been surveyed through support of RLS volunteers, massively expanding the program's geographic scope.

3.3. Management applications

3.3.1. Distribution of biodiversity

RLS survey data allowed the first systematic accounting of shallow reef biodiversity across the full AMP network (Stuart-Smith and Edgar, 2017). These data also provided an empirical basis for assessing the representativeness of each MPA relative to other reefs across northern Australia, and worldwide.

Biogeographic relationships for fishes and macroinvertebrates between four Australian regions with AMPs, and tropical regions elsewhere in the Indo-Pacific, are depicted as a multidimensional scaling (MDS) plot (Fig. 4a). Unexpectedly, the Coral Sea region grouped much more closely with Tonga and the Marshall Islands (~3000 km distant) than with the Great Barrier Reef (~100 km distant). Clearly, most biodiversity elements in the Coral Sea MP cannot rely on recolonization from the Great Barrier Reef Marine Park following disturbance. To a lesser extent, AMPs located off Australia's North West Shelf also aligned with the Coral Sea and isolated Pacific islands, demonstrating the existence of a large assemblage of species characteristic of isolated Indo-Pacific islands. This oceanic biota contrasts with biota in AMPs in the Inshore North region and subtropical atolls in the Temperate East region, and also with a distinctive Wallacean biota that includes East Timor, Papua New Guinea, Solomon Islands and Vanuatu (Fig. 4a).

The inshore/offshore divide in Australian waters is more clearly apparent in an MDS plot relating sites in different AMPs with adjacent regions (Fig. 4b). Oceanic locations (Mermaid MP, Ashmore Reef MP, Rowley Shoals, Christmas Island, and Coral Sea MP) group together in the top right of the plot, regardless that they encompass locations in both Indian and Pacific Oceans. With the exception of Christmas Island and inshore reefs around north-western Australia (Kimberley) and northern Australia (North), AMP locations fill outlying points on the plot. Thus, almost all reef community types present on Australian coral reefs are encompassed within the AMP network. Species closely associated with inshore reefs (i.e. Kimberley, North, Pilbara) fall within state government jurisdictions (which extend 3 nautical miles offshore), and are therefore outside the remit of AMP managers. The Oceanic Shoals MP in the Timor Sea and subtropical Norfolk MP comprise biogeographic outliers, each with distinctive biodiversity elements to be prioritised for maximum protection if the AMP network is to safeguard all community types.

3.3.2. Sea snake population monitoring

RLS survey data describe population distribution and trends for common reef species present in AMPs, including recognised threatened species and those in need of listing. For instance, Australia is regarded as the centre of sea snake diversity worldwide (Lukoschek et al., 2013). Sea snakes include threatened and potentially threatened species, and RLS has revealed distribution gaps and declines. In the Coral Sea MP, multiple sea snake species are observed at RLS sites in the southern region (Ceccarelli et al., 2013), but no sea snakes have been observed on reefs north of Marion Reef through the large central region (Fig. 5a). In north-western Australia, no sea snakes were sighted during RLS voyages in 2012 (12 sites surveyed) and 2017/18 (20 sites) at Ashmore Reef, a location once regarded as the centre of sea snake abundance (Lukoschek et al., 2013). Sea snakes were, however, present at sites on reefs adjacent to Ashmore Reef. Densities of sea snakes at Marion Reef, the northernmost and warmest sea snake stronghold in the southern Coral Sea, declined >80% between 2012 and 2017 (Fig. 5b,c), with two dead animals observed ashore immediately after the 2016 heatwave (Fig. 5d).

Ongoing tracking of population trends for sea snakes and co-occurring animals should allow testing of different hypotheses related to population decline (e.g. warming temperatures, shark predation, loss of food resources).

3.3.3. Recovery of fish biomass

By definition, the primary goal of MPAs is biodiversity conservation

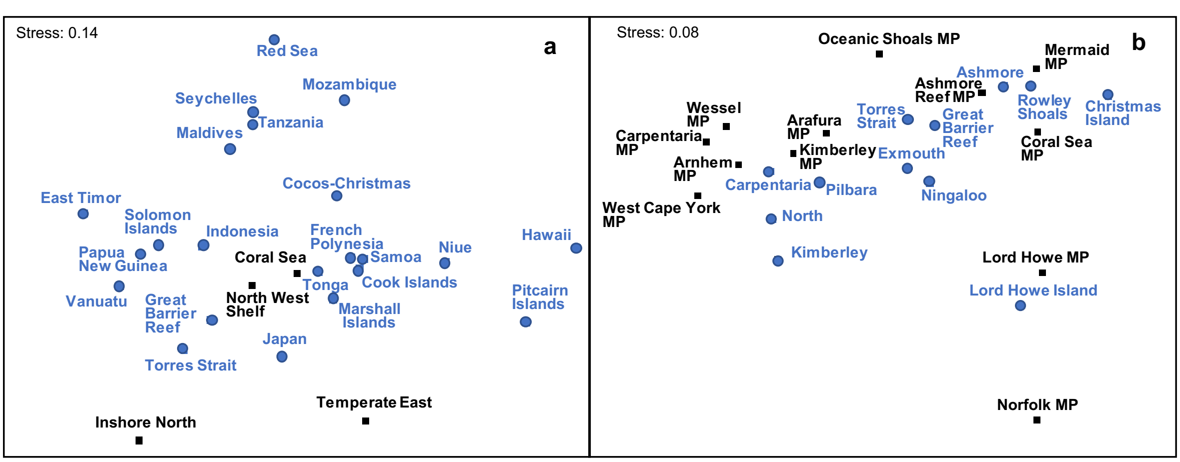

Fig. 4. a) Biotic relationships between reef communities surveyed by RLS divers in four regions with Australian Marine Parks (Coral Sea, Inshore North, North West Shelf, Temperate East; black squares) and tropical regions elsewhere in the Indo-Pacific (blue circles). b) Biotic relationships between reef communities surveyed by RLS divers in tropical Australian Marine Parks (black squares) and nearby regions (blue circles). Mean densities of fishes and mobile invertebrates at each site were log (x + 1) transformed, then the mean of sites with each region calculated. The similarity matrix relating pairs of sites was based on the Bray-Curtis index. MP: Marine Park. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

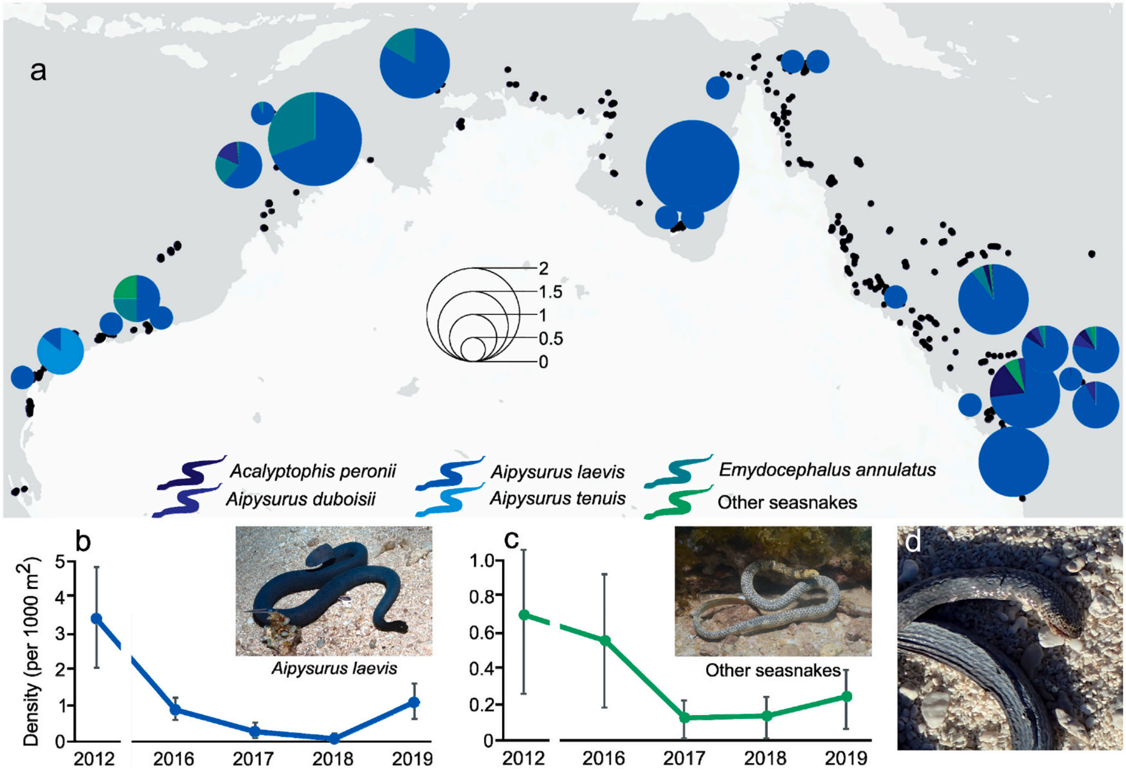

Fig. 5. a) Density of sea snake species across northern Australian sites censused by RLS divers. Small dark circles indicate no sea snakes observed. Plots shows mean density (± SE) of (b) olive sea snakes (*Aipysurus laevis*), and (c) other sea snakes at seven Marion Reef sites surveyed by RLS divers in five separate years. d) A dead olive sea snake, observed ashore at Paget Cay on 8 June 2016, immediately after the first major regional marine heatwave.

(Sobel, 1993). Where assisting biodiversity protection, MPAs also allow sustainable use of natural resources, such as by fishing (Day et al., 2019). Increased regulation of fishing in MPAs should nevertheless leave more fish in the sea, facilitating an increase (or at least stability) in total biomass of fishes, particularly large heavily exploited species (Edgar et al., 2014). Trophic cascades and other ecosystem changes (e.g. higher coral cover) may accompany an increase in biomass of large fishes, but if fish biomass does not change then other flow-on effects cannot be expected. Thus, total fish biomass is an important indicator of MPA zone effectiveness, and fish biomass recovery is also a necessary condition for other MPA-associated changes.

Little recovery of fish biomass is currently expected in new AMP protected zones as regulations were enacted only recently (July 2018). Nevertheless, almost all coral reefs in the AMP network with full fishing prohibitions were initially protected over 20 years ago. Changes in fish biomass over the past ~5 years for AMP coral reefs with long-established 'no-take' protection are shown in Fig. 6.

Total fish biomass increased through time in no-take zones at Ashmore Reef and Lord Howe MPs, remained stable at Mermaid MP, and declined at the Coral Sea MP (Fig. 6). In all cases, the trend was positive relative to change in nearby regulated fishing or general fishing zones (where fish biomass often declined), indicating progress towards achieving conservation goals.

The greatest rise in fish biomass was in the Ashmore Reef MP, where

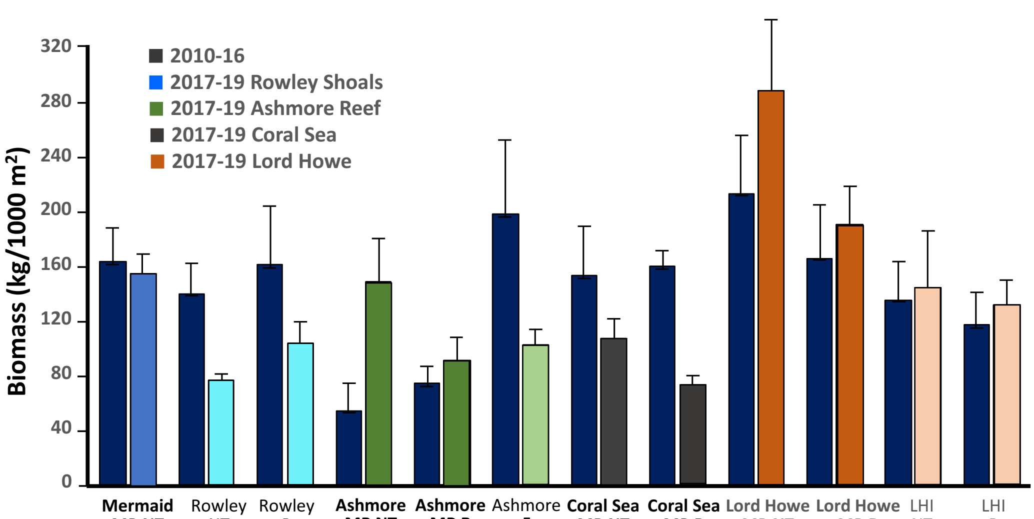

Fig. 6. Mean (± SE) total fish biomass of fishes observed in Australian Marine Parks (bold lettering) and comparable nearby reference regions. Biomass was calculated using estimated lengths of individual fishes sighted on RLS transects, and length/weight relations, as described in Edgar et al. (2014). Data were averaged through two periods – 2010-16 (solid dark blue bars) and 2017–19. MP: Marine Park, NT: 'no-take' (solid fill), R: restricted fishing (hatched), F: open to fishing (hatched); Rowley: Rowley Shoals state marine park, LHI: Lord Howe Island state marine park. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recent establishment of a permanent border security presence has likely contributed through strong enforcement of fishing prohibitions. Ashmore Reef MP sites that are open to restricted fishing showed less improvement in fish biomass, whereas nearby fished sites (Hibernia, Seringapatam and Scott Reefs) showed substantial declines. Fishing effort possibly moved from Ashmore Reef to nearby reefs as a result of the strong policing presence.

Fish biomass also increased in the no-take zone in the remote Lord Howe MP (i.e. Middleton Reef), with lesser increases in the restricted fishing zone (Elizabeth Reef) and in the New South Wales state-government administered Lord Howe Island Marine Park. Biomass was stable in the Mermaid MP, but declined in the two nearby Rowley Shoals MPAs that are state-government managed.

Declines in fish biomass in the Rowley Shoals and Coral Sea 'no-take' zones may reflect broad-scale impacts of heatwaves or cyclones. Alternatively, they could reflect offshore expansion of fishing effort and difficulties in enforcement of regulations at remote locations. This possibility warrants further investigation.

3.3.4. *Effects of coral bleaching*

The expansive geographic and taxonomic coverage provided by RLS has facilitated unique insights into the distribution and scale of coral bleaching impacts (Edgar et al., 2020), both across the full span of the AMP network and also the large adjacent Great Barrier Reef MP and Ningaloo MP (State waters). Comparison of data collected before and after the extreme 2016 bleaching event revealed declines of up to 51% in live coral cover on the reefs that experienced extreme temperatures across the Great Barrier Reef and western Coral Sea, with consistent associated declines in coral-feeding fishes (Stuart-Smith et al., 2018). Additional ecological changes were detected that linked directly to warmer sea temperatures rather than coral loss, including population increases for many fishes.

3.3.5. *Public education*

Through collaboration involving RLS, Parks Australia and the NESP Marine Biodiversity Hub, infographics and other educational products are now available that describe the biodiversity values of AMPs. Examples of online content with information and photographs provided by RLS divers are *'Colours of the Coral Sea'* (https://www.nespmarine.edu.au/document/colours-coral-sea) and *'Australian Marine Parks/Science'* (https://parksaustralia.gov.au/marine/science/).

4. Future challenges and opportunities

4.1. *Accounting for data errors and biases*

A detailed understanding of interactions between reef species, and improved development of quantitative food web models, requires accurate density estimates standardized by seabed area for different taxa. To achieve this goal, biases that affect underwater visual censuses (Section 2.2.7) need to be quantified, and corrections applied, such as by cross-validating transect observations with independent counts obtained using camera-traps and other methods, and use of capture-mark-recapture techniques (e.g. Edgar et al., 2004b).

4.2. *Expansion of global monitoring*

Successes of the RLS monitoring program in Australia could be readily expanded worldwide through establishment of similar citizen science groups. Global-scale monitoring would also be possible through increasing the RLS offshore survey fleet from one to four cost-effective sailing vessels crewed by volunteers (annual total cost ~\$1 million per year, 2500 sites surveyed; Fig. 7). The Argo float program (Roemmich et al., 2009) provides the inspiration for an expanded RLS effort. Argo data have revolutionised oceanography by providing a synoptic global picture through thousands of regular observations distributed haphazardly in space. A global RLS monitoring program would provide arguably the single-most important, cost-effective, and informative reporting tool on global marine biodiversity targets for relevant Sustainable Development Goals and the Convention on Biological Diversity.

4.3. *Integration with other scientific initiatives*

Observational studies such as RLS and the Australian Institute of Marine Science Long Term Monitoring Program (Emslie et al., 2020) allow the formulation of plausible hypotheses on influences of natural

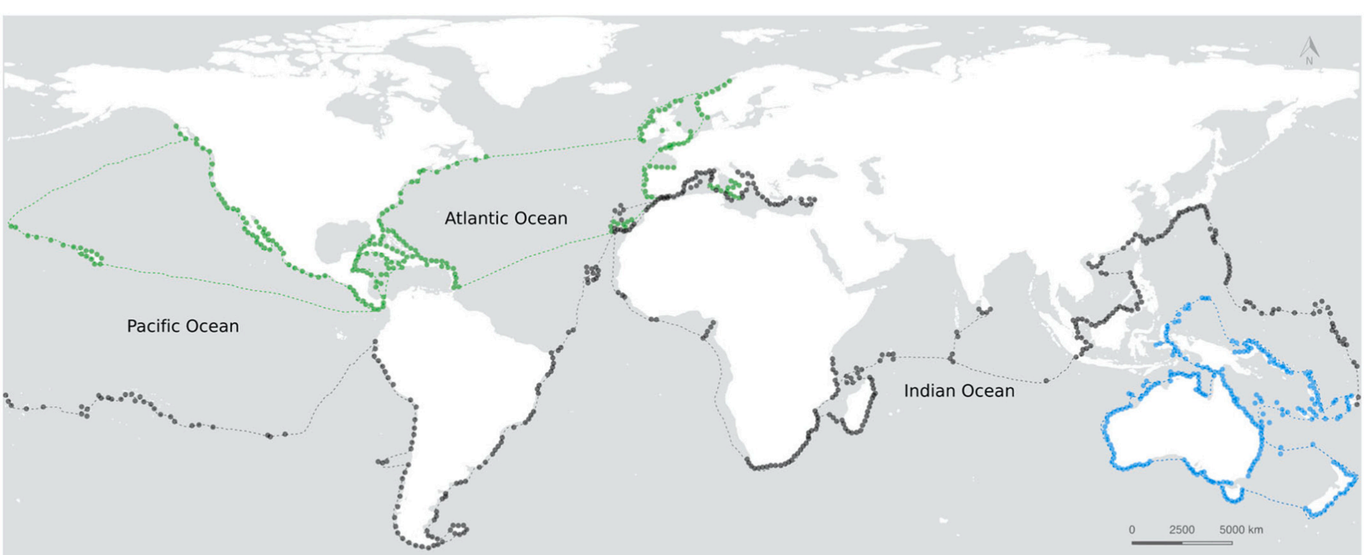

Fig. 7. Proposed expanded RLS global monitoring program involving four offshore sailing vessels crewed by volunteers, with >5000 sites repeatedly surveyed each two years. Two vessels track each other two years apart on a four-year global circumnavigation (black track: Europe-South America-Pacific Ocean-southeast Asia-Indian Ocean-Africa-Europe), the third vessel completes a two-year circuit of Australia and Melanesia (blue track), and the fourth vessel travels across the north Atlantic and north Pacific each two years (green track: Europe-Caribbean-eastern tropical Pacific-Hawaii-western North America-Caribbean-eastern North America-Europe). Higher latitudes are surveyed in summer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and anthropogenic stressors. Manipulative experiments are then needed to distinguish between alternative hypotheses and to establish causality. Coordinated experimental networks, with standardized experiments set out globally, are a powerful emerging ecological tool that combine controlled manipulations with observational data from natural systems (Duffy et al., 2015). RLS provides a global observational footing upon which such trans-continental experiments can be framed, such as deployment of standardized field assays to quantify predation and herbivory rates (Duffy et al., 2016b; Ling et al., 2018a).

Wide application of new metagenomic technologies is revolutionising ecology, allowing rapid characterisation of community structure and function (Leray and Knowlton, 2015), with taxonomic breadth that potentially allows microbial processes to be linked to function in fish, invertebrate, algal and unicellular eukaryote communities. However, major gaps exist in field validation, and in obtaining quantitative as opposed to qualitative estimates of animal abundances. Species-rich RLS abundance data can play a major role in filling these gaps, with cross-comparison trials presently underway (Bessey et al., 2020).

The quantitative nature and wide taxonomic scope of RLS data make them particularly useful for input into food-web models (Okey et al., 2004; Watson et al., 2013), including biomass-balanced trophic models that link consumption between organisms of different body size (Soler et al., 2018). Once modelled relationships are computationally streamlined, food webs generated for hundreds of RLS sites can be united into indices of coastal health, including transfer metrics between trophic groups. Such indices allow managers to advance from mapping of species and threats to tracking ecosystem function.

By combining quantitative RLS outputs, socio-economic data, and knowledge of energy systems, linkages between human activities and ecosystem state can be identified (Lazzari et al., 2020; Turnbull et al., 2020), as in a recent 'bright spots' study showing how fishing communities can successfully confront drivers of change (Cinner et al., 2016). Such socio-ecological models have huge potential to understand and forecast human drivers affecting biodiversity, and how change in biodiversity affects human society. Expanded model outputs should allow managers to assess cost-effective options when dealing with threats, and to identify where slight changes in human behaviour could improve environmental outcomes.

5. Conclusion

Many capable and enthusiastic recreational divers are keen to contribute to marine conservation efforts. Coordination of a subset of such divers, trained to rigorous data-collection standards, is enabling a positive change in science, conservation management, and how the public sees the marine world. Global-scale long-term data on species abundances at thousands of sites complements the current research emphasis on use of expensive technically complex methods for data collection. In contrast to the limited timespan of most projects, where outcomes generally fade in importance over subsequent years (as evidenced by rapid peak then decline in journal citations, Glänzel and Moed, 2002), the value of the global RLS dataset will increase each year as a quantitative global standard against which biodiversity change in inshore marine ecosystems is measured. Funding is presently the greatest limitation in achieving continuous global marine monitoring with Reef Life Survey, and thus for reaching its full potential to advance conservation.

Declaration of competing interest

Authors have no perceived conflicts of interest other than the following:

Rick-Stuart Smith is President and Board Member of Reef Life Survey Foundation.

Graham Edgar, Margo Smith and Peter Mooney are Board Members of Reef Life Survey Foundation.

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