Marine Biological Surveys of Coral Reefs in the Northern Lau Group

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Photograph (front cover): Vatuvara Island in the Northern Lau Group
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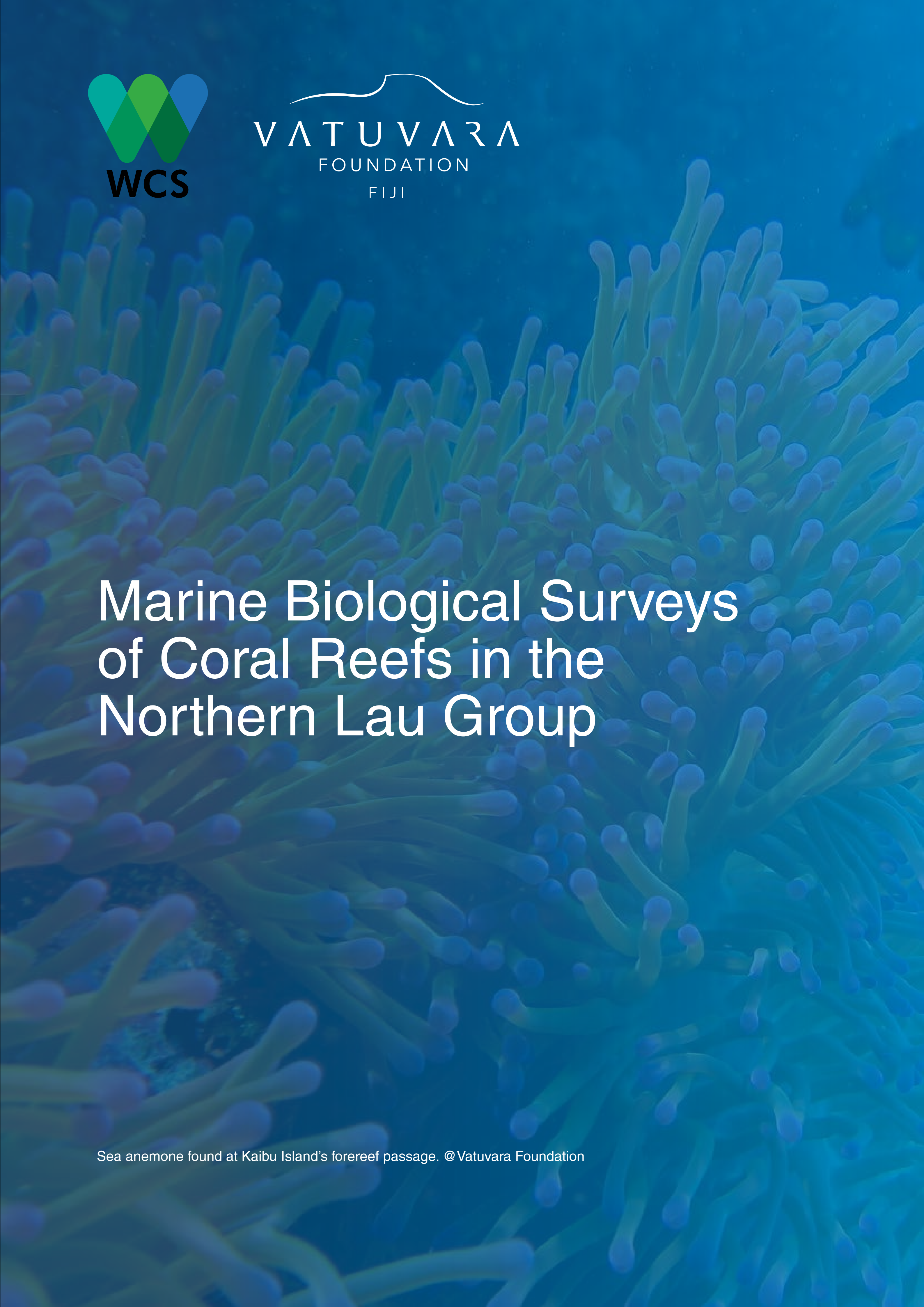

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Sea anemone found at Kaibu Island’s forereef passage. @Vatuvara Foundation

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EXECUTIVE SUMMARY

The province of Lau, located in Fiji's Eastern Division, comprises 60 islands and islets collectively known as the Lau Group. The Lau Group has been identified as an area of national significance and high priority for marine protection. On 20 February 2016, Fiji was hit by Category 5 Tropical Cyclone Winston that caused widespread damage across the country. Cyclone Winston made first landfall through the Eastern Division, severely damaging the islands and diverse ecosystems of Northern Lau.

An 8 day marine biological baseline survey was conducted by Vatuvara Foundation and the Wildlife Conservation Society (WCS) from 8–16 May, 2017. The expedition was the first systematic effort to document the marine environments of Kaibu, Yacata, Vatuvara, Kanacea and Adavaci islands in the Northern Lau Group. The objectives of this survey were to: (a) collect data on the health, abundance and diversity of corals, reef fish and invertebrate species, in order to establish a baseline for long-term monitoring; (b) document the damage to community fishing grounds caused by Cyclone Winston; and (c) provide recommendations to communities on the management of their traditional fishing grounds to support food security and sustainable livelihoods.

A total of 33 sites of varying habitats were surveyed, including lagoon patch reefs, channels, and leeward and windward island fringing reefs. Profiles of each site were made to describe the reef type, current(s), exposure, reef structure and relief, habitat complexity and general observations. The reefs showed results of the extreme isolation of these islands, pounded on windward sides by the large ocean swells of the Pacific with sheltered leeward sides. A total of 47 coral genera were found across the sites, including massive and submassive *Porites, Platygyra, Favites* and *Acanthastrea corals*; and branching, plates, tabular and encrusting coral forms of *Pocilliopora, Stylophora, Turbinaria,* and *Acropora*. The effect of Cyclone Winston was apparent on more than half the reefs sites surveyed. Hard coral was the dominant substrate with the highest cover recorded at Vatuvara Island (27.9%) and lowest at Adavaci Island (9.1%). Reef systems in Northern Lau appeared to show a high degree of resilience to natural disturbances, likely a result of their exposure to extreme wave action and weather conditions.

A high number of fish species (293) was recorded during the survey. Overall, fish populations showed high diversity within the families *Labridae, Pomacentridae, Chaetodontidae, Acanthuridae* and *Scaridae*. Mean fish biomass across all sites was remarkably high (1095.1 kg ha^{-1}), with Vatuvara Island supporting the highest biomass (2180.3 kg ha^{-1}). Maintaining fish biomass above these reference levels promotes sustainable fish populations. Populations of at least eight species listed on the 2017 IUCN Red List of threatened species were observed, including the globally endangered humphead wrasse (*Cheilinus undulatus*), four shark species and the endangered green turtle (*Chelonia mydas*) and hawksbill turtle (*Eretmochelys imbricata).*

Invertebrate populations were notably low, especially giant clams, sea cucumbers, crustaceans and urchins.

The biological data collected establishes a baseline understanding of the marine environment of the remote islands surveyed. The data will be used as reference for the long-term monitoring of these marine environments to detect potential changes. The suite of early warning indicators of coral health and supporting water quality monitoring will help interpret changes to these critical marine habitats. The findings from this study will be used to help revive and guide ocean conservation in Northern Lau through a network of community locally-managed marine areas, provide innovative solutions that promote environmental awareness and empower local communities to better manage their natural resources.

The study recommended:

i. Actions should be taken to minimize human-stresses to coral reefs, especially areas that were impacted by Cyclone Winston;
ii. Protection of coral reefs that were undamaged, which may play a critical role in the recovery of adjacent impacted reefs;
iii. Recommendations to communities of key areas for conservation, including sites for inclusion in proposed networks of Locally-Marine Managed Areas (LMMAs) or Marine Protected Areas (MPAs) should be provided. Planning should be done in consultation with communities, respecting the traditional values, needs and aspirations of communities;
iv. Establish MPAs that are easily enforceable and targeting areas that are diverse, unique and provide refuge for threatened species;
v. Livelihood programs for communities should be developed in order to relieve pressures from marine resources and support sustainable futures;
vi. A surveillance and enforcement strategy should be implemented to reduce threats to coral reefs; and
vii. A monitoring program to measure the recovery of coral reefs should be implemented over the next 2–5 years, and ensure it is linked to management actions.

1.0 INTRODUCTION

The Lau Group comprises 60 islands and islets totaling 487 km^2, scattered over 114,000 km^2 of relatively pristine ocean (Fig. 1). The islands were formed as a result of Miocene and early Pliocene island arc volcanism. A major tectonic event caused the splitting of the Lau-Tonga arc that eventually formed the Lau Basin through sea floor spreading, leaving the Lau ridge a remnant arc (Woodhall, 1985). The active volcanoes that formed the islands underwent a period of subsidence, and the Lau Ridge became covered by shallow-water reef limestone. The island arc began rising, lifting the reef limestone overlying volcanic rock to its current position (Nunn, 1987).

Traditionally, Lauans were seafaring people, devoting their time and resources to building the Fijian canoe (*drua).* During the eighteenth and nineteenth centuries, the Lau Group was the centre of trading between Fiji, Tonga and Samoa, and was known for its rich *vesi* (Pacific teak, *Intsia bijuga*) reserves and canoe craftsmanship (Nuttall et al., 2014). Canoe-building traditions in Fiji were rarely deployed after the 1970s, resulting in a huge decline in exchange of tradition and trade with most of Lau's population living on the larger islands of Vanua Levu and Viti Levu. The islands remain relatively isolated and underdeveloped. Providing sustainable livelihood options together with community owned conservation programmes has remained a challenge.

The Lau-Tonga corridor was recognized as "very high" priority in the 2011 Action Plan for implementing the Convention on Biological Diversity's Programme of Work on Protected Areas (Government of Fiji, 2011). The Fiji Islands Marine Ecoregion planning identified the southern Lau Group as one of five areas ranked to be globally important due to their uniqueness, endemism and high levels of diversity (Nair et al., 2003). The Lau Group was also included in the Fijian Government and partners' commitment at the United Nations Ocean Conference in New York from 5–9 June, 2017, to implement a series of integrated terrestrial and marine managed areas, operating under a co-management framework by 2025 (#OceanAction19904).

Understanding the biological resources of the Lau Group is critical for determining conservation management actions. Four marine surveys have been conducted in the Lau Group over the last decade. In September to October 2007, marine surveys carried out of fish, benthic cover, and invertebrate population around the islands of Wailagi-lala, Kibobo, Malima, Sovu, Vanua Balavu, Kanacea, Tuvuca, Aroua, and Katafaga by the University of the South Pacific, NatureFiji-MareqetiViti, Department of Fisheries, Department of Forestry and National Trust of Fiji, documented 333 fish species (48 families) and 131 species of hard corals (Anon., 2008). In 2008, the coral reefs of Ono-i-Lau, the southern-most island in the Lau Group was surveyed but little quantitative data was presented in the report (Fiu and Tokece, 2008).

In June 2013, the Living Oceans Foundation did comprehensive surveys of coral reefs around the islands of Totoya, Matuku, Moala, Fulaga, Kabara, Vanua Vatu, Nayau, Tuvuca, Cicia, Mago, and Vanua Balavu (Jupiter et al., 2013; Bruckner, 2014; Bruckner et al., 2016). Habitats were mapped and data were collected on fish, coral and motile invertebrates, as well as research on coral stress, metabolics, and ocean acidification. The majority of the substrate found was reef pavement (41–61% cover) and live coral (22–50% cover), with *Acropora* dominating in living cover (35%) (Bruckner et al., 2016). Total mean biomass of reef fish was moderately high (1126 kg ha^{-1}, range 801–1941 kg ha^{-1}) (Bruckner et al., 2016).

These earlier studies found sea cucumbers and giant clams were in very low abundances as far back as 2007 (Anon., 2008), with more recent surveys recording further declines in populations (Jupiter et al., 2013; Bruckner et al., 2016). While sites closest to human settlements were often in poorest health, these sites are also the easiest to protect and manage in community *tabu* areas, where they can be observed (Jupiter et al., 2013). The majority of islands were in southern Lau and very few were surveyed in the north.

During the initial resort construction of the exclusive resort Vatuvara Private Islands on Kaibu Island, an environmental impact assessment of marine resources was conducted over four days in January 2011 (Sykes, 2011). This assessment characterized the marine habitats, coral reef communities, fauna, and flora adjacent to the proposed development site (west coast of Kaibu Island) and up to 100 m either side of the site, using a host of methods including manta tows, quadrats, reef check surveys, and fish census. The lagoon flats were found to support very little live hard coral (18–26%) or invertebrate species (Sykes, 2011). The outer walls had low-relief coral cover, with higher coral cover (56%) found in the natural passages and gullies (Sykes, 2011). Although, few large sessile invertebrates were seen, several giant clams (*Tridacna squamosa*) and sea cucumbers (*Bohadschia argus*) were found on outer wall sites. The area surveyed was identified to have relatively large shark populations, suggesting this reef system may be an important conservation area for sharks and other pelagic species (Sykes, 2011).

Prominent vertical summit of Vatuvara Island overlooking lagoon and fringing reef. @Vatuvara Foundation

No comprehensive marine biological surveys of corals or fishes had been undertaken around the islands of Kaibu, Vatuvara, Yacata, Kanacea and Adavaci in the Northern Lau Group in Fiji's Eastern Division. Four of the islands are privately owned and under the management of Vatuvara Private Islands, while Yacata Island is customary land and adjacent coral reefs are under customary marine tenure. Kaibu Island is organically certified and is approximately 225 km east of Viti Levu and 50 km west of Vanua Balavu. Kaibu, along with the larger neighboring island of Yacata and islets, is within a single barrier reef system with a shallow, sandy lagoon between the islands, and channels connected to the open ocean. There is a single village on Yacata, facing Kaibu, with approximately 250 inhabitants. The uninhabited Vatuvara Island lies roughly 18 km south of Kaibu, covered in overgrown forest over karst limestone, with a prominent vertical summit. The unoccupied Adavaci Island lies within the Bay of islands near the mainland island of Vanua Balavu. Kanacea Island, the largest of the islands surveyed is approximately 15 km south west of Adavaci Island and has been developed for certified organic agriculture and livestock grazing. The islands support diverse native flora and fauna of notable and vulnerable conservation significance with several globally endangered and endemic species.

On 20 February, 2016 Fiji was hit by Category 5 Tropical Cyclone Winston with wind speeds of 233 km/hr and gusts of 306 km/hr (Government of Fiji, 2016). It was the largest cyclone recorded in the Southern Hemisphere, causing widespread damage across Fiji and the government declared a state of emergency following the event. Cyclone Winston impacted 540,400 people and the livelihoods of 62% of the population (Chaston-Radway et al., 2016). Cyclone Winston made first landfall in the Eastern Division, severely damaging the islands and coral reefs of Northern Lau. The cyclone destroyed food, agricultural crops, fisheries and ecosystems on a large scale. However, no studies were done in 2016 on the impact to coral reefs in the Lau Group.

In May 2017, Vatuvara Foundation and the Wildlife Conservation Society (WCS) partnered to undertake baseline surveys to: (a) collect data on the health, abundance and diversity of corals, reef fish and invertebrate species; (b) establish a baseline for long-term monitoring; (c) document the damage to community fishing grounds caused by Cyclone Winston; and (d) provide recommendations to communities on the management of their traditional fishing grounds to support food security and sustainable livelihoods. These data are critical for identifying areas of concern where conservation strategies and management actions are needed, and will guide the conservation work of the Vatuvara Foundation.

2.0 METHODS

2.1 Survey sites

Coral reef surveys were conducted in the Northern Lau Group over 8 days from 8–16 May 2017, on SCUBA, using WCS's Standard Monitoring Protocol (WCS, 2010) and the IUCN Resilience Assessment Protocol (Obura and Grimsditch, 2009). The surveys were designed to be a rapid assessment, to cover covering windward, leeward and lagoonal patch reefs. Leeward facing reefs were generally on the Northern side of the islands while windward reefs faced southeast. A total of 33 sites were surveyed on coral reefs around the islands of Kaibu, Vatuvara, Yacata in Cakaudrove Province, and Kanacea and Adavaci in Lau Province (Fig. 1, Table 1), at 8–12 m depth across a diversity of exposures and coral reef types. A total of 14 leeward sites, 11 windward sites and 8 lagoonal sites were surveyed. The lagoonal sites were between Kaibu and Yacata islands (3 m), and at Vatuvara (2 m) and Kanacea islands (0.4 m, 2.5 m).

Site descriptions were made during each dive to record reef type, current, exposures, reef slope, habitat complexity and general observations about the site, including the composition of the coral community (Appendix 1). During each dive, notes were taken on the level of damage observed at each site, focusing on the genera of coral most affected, scouring of surfaces, presence of new turf algae and rubble fields.

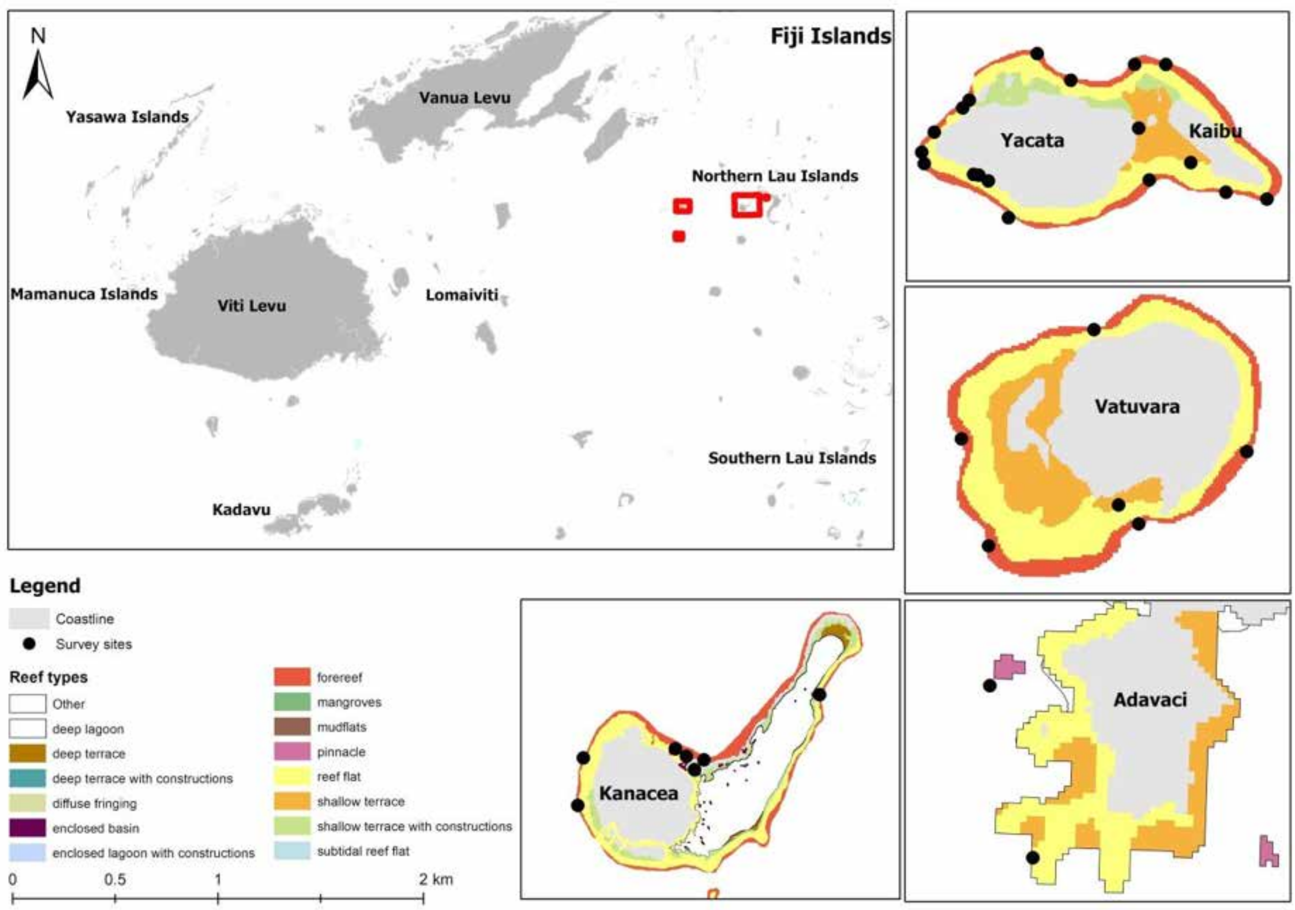

Figure 1. Map of Fiji Islands and the sites surveyed around five islands in the Northern Lau Group.

Table 1. Coral reef sites surveyed in the Northern Lau Group. Sites with an asterisk will be included as part of the Vatavara Foundation's long-term coral reef monitoring plan for the three largest islands.

Date	Island	Site Name	Site Code	Reef Type
08/05/2017	Yacata	Filo's Mooring	YAC15	Leeward Forereef
08/05/2017	Yacata	Filo's Passage	YAC13	Leeward Forereef
09/05/2017	Yacata	Daku's Passage	YAC07	Leeward Forereef
09/05/2017	Kaibu	Kaibu Point	YAC09	Leeward Forereef
09/05/2017	Kaibu	GM's Point	YAC11	Lagoon Patch Reef
09/05/2017	Yacata	Yacata Point*	YAC06	Leeward Forereef
09/05/2017	Yacata/Kaibu	Kaibu Passage*	YAC08	Leeward Forereef
09/05/2017	Yacata	East Yacata Lagoon	YAC05	Lagoon Patch Reef
10/05/2017	Yacata	Turtle Beach*	YAC16	Leeward Forereef
10/05/2017	Yacata	Yacata Coral Corner	YAC01	Leeward Forereef
11/05/2017	Yacata	Tabu Shallows*	YAC17	Lagoon Patch reef
11/05/2017	Yacata	Porites Path*	YAC18	Lagoon Patch Reef
12/05/2017	Kaibu	Surgeon Slide	YAC04	Windward Forereef
12/05/2017	Yacata/Kaibu	QereQere	YAC03	Windward Forereef
12/05/2017	Yacata	Tabu Point	YAC21	Sheltered Windward Forereef
12/05/2017	Kaibu	SE Kaibu Point	YAC19	Windward Forereef
12/05/2017	Yacata	Opposite Tabu*	YAC02	Windward Forereef
12/05/2017	Yacata	West Yacata Corner	YAC20	Windward Forereef
13/05/2017	Vatuvara	Picnic Beach Reef	VATU01	Lagoon Patch Reef
13/05/2017	Vatuvara	Windward Beach	VATU05	Windward Forereef
13/05/2017	Vatuvara	World class*	VATU04	Leeward Forereef
13/05/2017	Vatuvara	Picnic Beach Drop Off	VATU06	Sheltered Windward Reef
13/05/2017	Vatuvara	Hidden Jewel*	VATU02	Sheltered Windward Reef
13/05/2017	Vatuvara	Diversity Drop*	VATU03	Leeward Forereef
14/05/2017	Kanacea	Pinnacle Point	KAN07	Leeward Forereef
14/05/2017	Kanacea	Blue Sea Star Lane	KAN03	Lagoon Patch Reef
14/05/2017	Kanacea	Kanacea Entrance	KAN08	Leeward Forereef
14/05/2017	Kanacea	Channel*	KAN09	Lagoon Patch Reef
15/05/2017	Kanacea	Outer Reef Point	KAN04	Windward Forereef
15/05/2017	Kanacea	Spur and Groove*	KAN05	Leeward Forereef
15/05/2017	Kanacea	Coral Cover Point*	KAN06	Leeward Forereef
15/05/2017	Adavaci	Outer Main Beach	ADA04	Windward Forereef
15/05/2017	Adavaci	Patchy Shallows	ADA01	Lagoon Patch Reef

2.2 Benthic cover

Point intercept transects for benthic cover were recorded at 0.5 m intervals along 3 x 50 m transects, using a modified Global Coral Reef Monitoring Network category list (WCS, 2010). Coral identification was done to life form and genus level. Microhabitat complexity was recorded in a 0.5 m^2 area, every 0.5 m, using the following five point scale: 1=totally flat (e.g. sand), 2=rubble/small patches of vertical relief; 3=mounding structures; 4=submassive or coarse branching structure; and 5=complex branching structure with crevices in the reef. Every 5 m, macro-complexity was recorded by looking forward at the reef (in approximately a 5 x 5 m area), and evaluating on a five point scale where: 1=no vertical relief; 2=low, widespread relief; 3=moderate relief; 4=complex vertical relief; and 5=complex vertical relief with fissures, caves and/or overhangs. Benthic surveys were designed to detect significant differences in benthic cover between sites and habitats within sites that may influence fish and invertebrate abundance.

To collect a long-term record of benthic cover, 40–45 underwater photos were taken using a fixed camera-to-substrate distance of 0.5–1.0 m, holding the camera perpendicular to the substrate, just to the side or over the transect line. A second diver carried out a general survey 5 m either side of the transect to compile a list of genera present at the site, and a single list was generated for each of the islands visited (Appendix 2).

2.3 Fish surveys

Coral reef fish species, size and abundance were recorded in three 50 x 5 m belt transects, following the depth contour on the reef, attempting to stay on the reef substrate as much as possible. At least 5 m of space was left between each transect. All species were recorded in the families Acanthuridae (surgeonfish), Labridae (wrasses), Serranidae (groupers excluding anthias), Balistidae (triggerfish), Lethrinidae (emperors), Siganidae (rabbitfish), Caesionidae (fusiliers), Lutjanidae (snappers), Scombridae (mackerel and tuna), Carangidae (jacks and trevallies), Mullidae (goatfish), Sphyraenidae (barracuda), Chaetodonotidae (butterflyfish), Nemipteridae (breams), Sharks (all families), Ephippidae (spadefish aka batfish), Pomacanthidae (angelfish), Pomacentridae (damselfish), Haemulidae (sweetlips), Priacathidae (bigeyes), Kyphosidae (chubs and rudderfish), and Scaridae (parrotfish). The size of fish were recorded in the following classes (to nearest cm): 2–5, 6–10, 11–15, 16–20, 21–25, 26–30, 31–35, 36–40, and >40. For fish >40 cm, the number and the size of each of the fish was documented. Each transect took 15–20 minutes.

Where time allowed, a list (without abundance or size estimation) of all species seen during the survey dives was made, to record comparative biodiversity of non-cryptic fish.

2.4 Invertebrate surveys

Invertebrate species, size, and abundance were recorded in three 50 x 5 m belt transects, following the depth contour on the reef. At least 5 m of space was left between each transect. Searches were done in a zigzag pattern and all species that were ecologically important, commonly seen or typically targeted for consumption were identified to the highest level possible. The size of invertebrates was recorded in the following classes (to nearest cm): 2–5, 6–10, 11–15, 16–20, 21–25, 26–30, 31–35, 36–40, and >40. Each transect took 15–20 minutes.

2.5 Temperature and water quality monitoring

Onset HOBO (U22-001) water temperature loggers were installed at seven sites at shallow (2.5–5 m), and deep (9–18 m) locations (Table 2). Loggers were set to take sea surface temperature readings every 2 hours. Water quality was tested at seven sites using a suite of low-tech field tests including a submersible thermometer, a depth gauge, a hydrometer, and pH liquid indicator fluid. The depth, temperature, salinity, and acidity of water samples was recorded at each site where a logger was installed.

Karst limestone islands of the Northern Lau Group. @Vatuvara Foundation

Table 2. Temperature logger's details and locations installed in the Northern Lau Group.

Date	Serial Number	Island	Depth (m)	GPS Coordinates
05/10/2017	20066528	Kaibu	2.5	17° 15' 30.7" S 179° 29' 25.9" W
23/07/2017	20116233	Kaibu	12	17° 14' 29.2" S 179° 30' 21.5" W
12/08/2017	20116231	Yacata	5	17° 15' 51.4" S 179° 32' 12.4" W
11/08/2017	20116234	Vatuvara	3	17° 25' 23.3" S 179° 32' 17.2 "W
11/08/2017	20116232	Vatuvara	18	17° 25' 05.6" S 179° 31' 52.6" W
13/09/2017	20116229	Kanacea	9	17° 14' 38.3" S 179° 08' 25.4" W
13/09/2017	20116230	Adavaci	9	17° 12' 06.5" S 179° 00' 54.5" W

Hydrogen sulphide field tests were carried out to detect the presence or absence of coliform bacteria in surface water samples. Water samples were taken using aseptic techniques, in unopened sterile drinking water bottles, emptied at the sample site immediately before sampling, rinsed with seawater twice, and then filled with seawater. The presence or absence of bacteria from sewage or farm animal contamination was tested using indicator paper, which developed a black colour over time in the presence of hydrogen sulphide. The speed of colour change is proportionate to the number of coliform bacteria in the water (Sykes, 2013) (Table 3). Although, the test is not quantitative, results have shown that water that turns black in less than 24 hours correlates to over 100 bacteria per 100ml, whereas samples that take longer than 36 hours to develop black colouration usually contain less than 10 bacteria per 100ml (Sykes, 2013).

Table 3. Exposure time and relative levels of water contamination for hydrogen sulphide tests.

Exposure Time (hours)	Relative Bacteria Level
0–24	High
24–26	Moderate
36 +	Low

2.6 Statistical modelling

We used lme4 package (Bates et al., 2012) in R (R Core Team, 2017) to perform linear mixed effects analysis of the relationship between coral reef health and environment. Hard coral and unconsolidated substrate cover and fish biomass represented coral reef health while exposure to wind and different islands represented the environment. To investigate if location and exposure had an effect on hard coral and unconsolidated substrate cover and fish biomass, we modeled each of the variables as a function of location and exposure. Sites were used as a random effect to explain variability in coral cover, unconsolidated substrate and fish biomass across location and exposure. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. P-values were obtained by likelihood ratio tests of the full models with the effect in question against the model without the effect in question.

3.0 RESULTS

3.1 Reef descriptions

The coral reefs habitats surveyed were typical of the Lau Group, with steep outer walls exposed to high waves and extreme weather conditions, and a shallow (2–3 m) inner lagoon comprising mostly of sand, algae and seagrass flats, interspersed with patch reefs (Plate 1). The seagrass beds lining the coasts of the islands, are critical habitats for fish and invertebrate species, and are feeding grounds for the green and hawksbill turtles *(Chelonia mydas, Eretmochelys imbricata)* which were observed during multiple dives.

The windward facing reefs were characterized by distinctive spur and groove structures with large accumulations of boulder and rubble at the bases, potentially from Cyclone Winston. The reef slopes appeared damaged (e.g. extensive coral breakage, coral abrasion, dislodgement of large coral colonies and structural damage to the reef framework), had little relief with large areas of reef matrix, and were dominated by submassive and encrusting corals. Although coral diversity was low at windward sites, there was areas of available substrate for corals to settle.

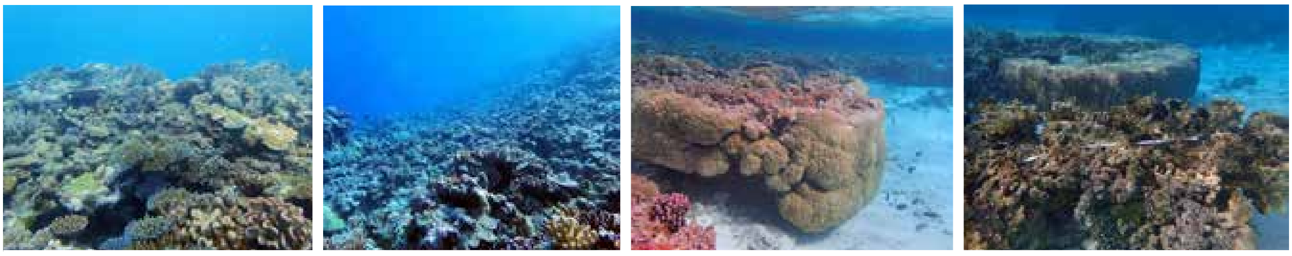

Plate 1. Left to right are examples of leeward, windward, lagoonal and backreef reefs at Kaibu, Yacata, Kanacea and Adavaci islands. ©Sangeeta Mangubhai/WCS

There were notable differences observed between leeward and windward facing coral reefs around the five islands surveyed. Leeward forereef sites were largely characterized by gentle slopes with distinctive deep crevices and grooves, sloping to a sandy bottom interspersed with patch reefs. These sites had diverse coral communities dominated by submassive, massive and tabulate forms of *Porites*; branching, staghorn corymbose, plating forms of *Acropora*; and branching *Pocillopora* species. A high diversity of reef building corals were recorded, largely from the family Faviidae (e.g. *Favia, Favites, Leptoria* and *Platygyra* species, Plate 2). Coral communities on leeward facing reefs provided diverse habitats for a wide range of reef species and did not show significant signs of damage.

Plate 2. Coral species dominating leeward sites. *Pocillopora* (left) found at Yacata Island. ©Sangeeta Mangubhai /WCS. *Acropora* (right) found at Kaibu Island. ©Vatuvara Foundation

Shallow lagoon patch reefs experience strong currents depending on the tide (K. Miller, pers. comm.). The lagoonal patch reef (YAC05) between Kaibu and Yacata islands was dominated by rubble with a high presence of microbial mats (i.e. green, red and brown cyanobacteria) covering rubble and sand. Many of the inner reef sites contained high macroalgae cover and dense buildup of microbial mats on the reef structure (Plate 3). One of the more noteworthy site surveyed was the Yacata Village's *tabu* (i.e. periodically harvested closure), which was closed in 2009 and reopened in 2013[1]. The *tabu* area was dominated by encrusting forms, branching and massive *Porites*, large stands of branching *Galaxea* and a spectacular formation of yellow foliose *Turbinaria* coral (Appendix 1). There were large schools of juvenile parrotfish, suggesting it was an important nursery area for this group of species.

Visible damage from Cyclone Winston was evident at 18 of the 33 sites surveyed, and was highest on windward facing reefs (see Appendix 1 for detailed site descriptions). Fifteen months after Cyclone Winston there were juvenile coral recruits (<5 cm) present, suggesting early signs of recovery. Large areas of crustose coralline algae were also recorded, critical for cementing the reef structure and forming a smooth surface for new coral settlement.

[1]On 10 October 2017, the community of Yacata Island declared this lagoonal habitat of their traditional fishing grounds as a no-take marine protected area. Yacata Village's tabu will be closed for another 5 years and the perimeter has been extended to include the outer fringing reef. The decision to close their reefs happened after education and awareness conducted by Vatuvara Foundation in partnership with the Wildlife Conservation Society and Ministry of Fisheries.

Plate 3. Microbial mats covering coral rubble in the lagoon between Kaibu and Yacata islands. ©Sangeeta Mangubhai/WCS

3.2 Benthic cover

Overall, 47 coral genera were recorded across the five islands. Kanacea Island had the greatest number of coral genera (41), followed by Kaibu and Yacata (39), Vatuvara (37) and Adavaci (28) (Appendix 2). A total of 19 common coral genera were recorded at all sites, including massive and submassive forms of *Porites, Platygyra, Favites* and *Acanthastrea*, and branching, plating and encrusting forms of *Pocilliopora, Stylophora, Turbinaria* and *Acropora*. Certain coral genera were only found at specific sites, including *Caulastrea* at Kanacea Island, *Pectinia* at Adavaci Island, *Tubastrea* at Vatuvara Island and *Podobacia* at Kaibu and Yacata islands.

Percent cover of hard coral, reef matrix (consolidated substrate), soft coral, algae, microbial mat, unconsolidated substrate and sponges were recorded at all sites. Hard coral was the dominant substrate, averaging 21.4% with the highest cover recorded at Vatuvara Island (27.9%) and lowest at Adavaci Island (9.1%) (Fig. 2A). Soft coral cover was the least abundant substrate type (Fig. 2B).

Despite damaged reefs being more notable on windward sides, there was no significant difference ($p>0.05$, Table 4) in average hard coral cover between leeward (24.9 ± 2.5) and windward (22.0 ± 4.3) sites surveyed. Moreover, 73.8% of variability in hard coral cover across the four islands surveyed was associated with location and exposure, while 10.1% was associated with sites. Although all islands had higher average coral cover than Adavaci, there was no significant difference in hard coral cover between islands ($p>0.05$, Table 4).

Low benthic cover for algal assemblages, macroalgae, sponges and other was found across all islands (Fig. 2F, 2D, 2K, 2J). Turf and calcareous algae cover across the islands was generally less than 10% (Fig. 2C, 2E). Microbial coverage, which consists largely of damaging cyanobacterial mats, were less than 10%, and were highest at Kaibu and Yacata islands (Fig. 2G).

Adavaci had very high cover for unconsolidated substrate (mean cover 70.0%) with a relatively low reef matrix (7.0%) compared to other islands (Fig. 2I, 2H). Location and exposure explained 86.4% of variance while sites accounted for 14.3% variability in unconsolidated substrate cover. Despite the high variability in unconsolidated substrate cover, the study did not find any significant difference between leeward and windward sides ($p>0.05$, Table 4). However, there was significant difference in unconsolidated substrate between islands ($p\leq0.05$, Table 4), largely due to the difference recorded in Adavaci.

Healthy hard coral cover surveyed around Kaibu Island. @Vatuvara Foundation

Table 4. The effects of location and exposure on the percent cover of benthic categories and fish biomass (kg ha^{-1}). A chi-square distribution test was used to obtain the p-value represented by the C-statistics. * indicates a significant difference ($p \leq 0.05$)

Variables tested	Environmental variable	C-statistics	p-value
Hard coral	Location	5.10	0.16
	Exposure	0.36	0.55
Unconsolidated substrate	Location	17.3	0.05*
	Exposure	0.42	0.51
Fish biomass	Location	4.56	0.21
	Exposure	1.59	0.20

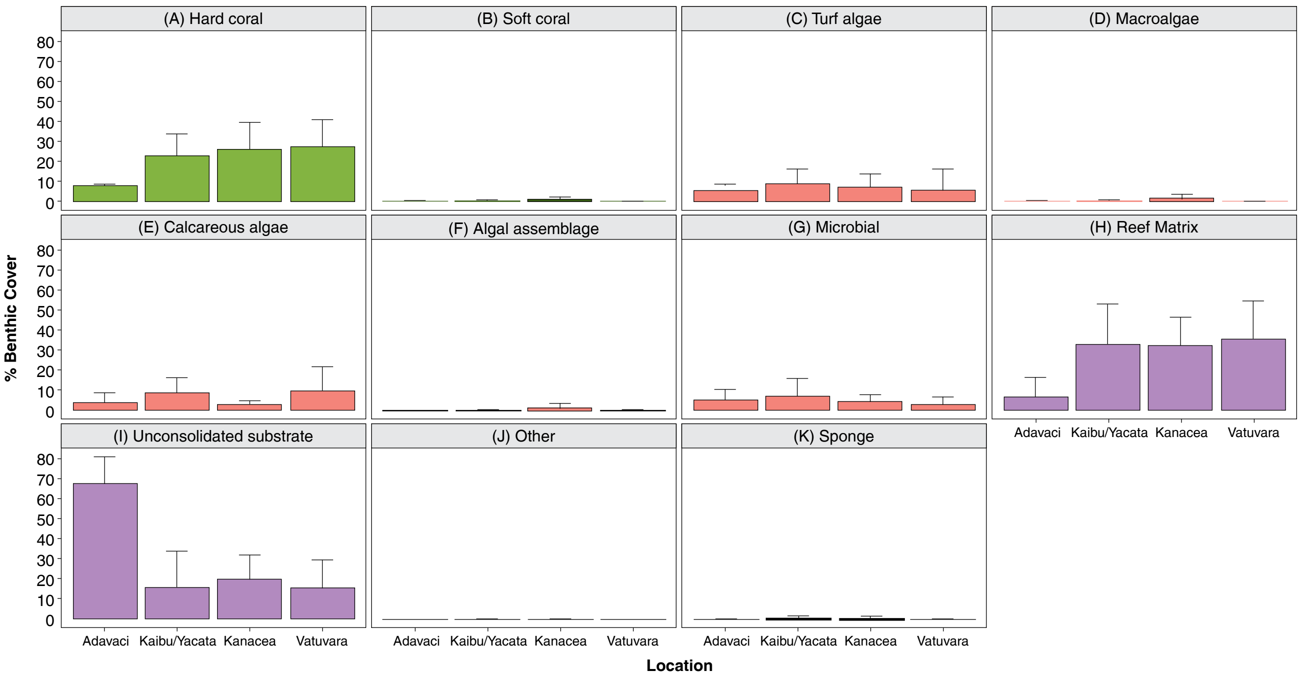

Figure 2. Average percent of benthic coverage for coral, algae, reef matrix, unconsolidated substrate, sponge and other surveyed at each island where error bars represent standard deviation.

3.3 Fish surveys

A total of 293 number of fish species were documented throughout the survey. Over the 33 sites surveyed, the greatest number of fish species was recorded at Kaibu and Yacata islands (n=249), followed by Vatuvara (n=201), Kanacea (n=185) and Adavaci (n=96) (Appendix 3). The most common families recorded were *Labridae* and *Pomacentridae*, followed by *Chaetodontidae*, *Acanthuridae*, *Scaridae*, *Mullidae*, *Lutjanidae* and *Serranidae* (Table 5, Appendix 3). Uncommon species seen included three species of unicornfish (*Naso tonganus, N. caesius, N. thynnoides*), a small school of *Alectis ciliaris*, and the unusual black phase of *Forcipiger longirostris.* The majority of the fish seen were herbivores, corallivores and planktivores, with some low-level predators. Although, *Muraenidae* (moray eels) and *Rajiformes* (rays and skates) were not recorded during the surveys, these species are commonly seen on leeward fore reefs and lagoonal patch reefs at Kaibu, Yacata and Vatuvara islands (K. Miller, pers. comm.). A total of 22 sharks (*Triaenodon obesus, Carcharhinus melanopterus, C. amblyrhynchos and Sphyrna mokarran*) were recorded across 12 sites. The endangered humphead wrasse (*Cheilinus undulatus*) was also recorded at 5 sites.

Table 5. Common fish families surveyed at each location.

Famliy	Common name
Labridae	Wrasses
Pomacentridae	Damselfish
Chaetodontidae	Butterflyfish, Bannerfish
Acanthuridae	Surgeonfish, Unicornfish
Scaridae	Parrotfish
Mullidae	Goatfish
Lutjanidae	Snappers
Serranidae	Groupers, Anthias, Soapfish

The average fish biomass for all sites surveyed provides an indication of the health of fish communities, fishing pressure, and a baseline for the long-term monitoring of these coral reef systems. The total mean biomass of fish for the five islands was 1095.1 kg ha^{-1}, and ranged from 347.9–2180.3 kg ha^{-1} across sites.

Despite Vatuvara Island having a higher average fish biomass (2180.3 kg ha^{-1}) than all other islands (Fig. 3), there was no significant difference in location for fish biomass ($p>0.05$, Table 4). In comparison, Adavaci Island had the lowest fish biomass (347.9 kg ha^{-1}) (Fig. 3). Windward sides had higher fish biomass (1309.6 kg ha-1) than leeward sides (983.0 kg ha^{-1}); however, the difference in exposure was not significant ($p>0.05$, Table 4). Location and exposure explained 63.6% variance while sites attributed to 7.5% variability in fish biomass across all islands.

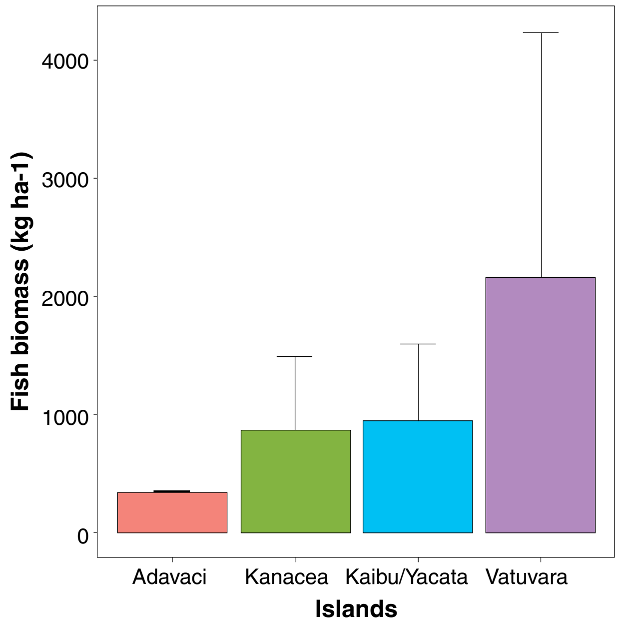

Figure 3. Average fish biomass (kg ha^{-1}) for each island surveyed where error bars represent standard deviation.

3.4 Invertebrate distribution

The abundance of invertebrates found was low and varied across sites and islands surveyed (Fig. 4). The vulnerable giant clams *Tridacna derasa, T. squamosa, T. maxima,* and *T. crocea* were recorded at Vatuvara, Kanacea, Kaibu and Yacata islands (Plate 4). Kaibu and Yacata islands had the highest abundance of giant clams, with a total of 24 recorded, followed by a total of 10 giant clams at Vatuvara Island and only a total of 3 giant clams at Kanacea Island. There was an average of 3.1 giant clams per site at each of the islands surveyed, although no giant clams were observed at Adavaci Island.

Plate 4. Giant clams *Tridacna derasa* (above) and *Tridacna squamosa* (below) observed at surveyed sites. ©Katy Miller/Vatuvara Foundation

A total of 21 sea urchins (*Diadema setosum*) were recorded at Kaibu and Yacata, the highest recorded among all islands (Fig. 4G). The highest abundance of sea stars (8 individuals) was recorded at Kanacea Island (Fig. 4H). Sea cucumbers, lobsters (e.g. *Panulirus versicolor*) and other crustaceans (e.g. *Dardanus guttatus*) had extremely low abundances or were absent from most sites (Fig. 4A, 4D, 4F). Sea cucumber species recorded were *Bohadschia argus, B. graeffei, Stichopus herrmanni, Actinopyga mauritiana* and *Pearsonothuria graeffei* (Plate 5).

Coral predators such as the cushion star (*Culcita novaeguineae*) and crown-of-thorns starfish (*Acanthaster planci*) were recorded but there was no evidence of population outbreaks (Plate 6). Sea stars (*Echinaster luzonicusm, Linckia laevigata*) were recorded in shallow lagoon patch reefs. Other invertebrates observed during surveys including the honey comb oyster (*Hyotissia hyotis*), tiger cowrie (*Cypraea tigris*), cone shells, sea anemones, and nudibranchs.

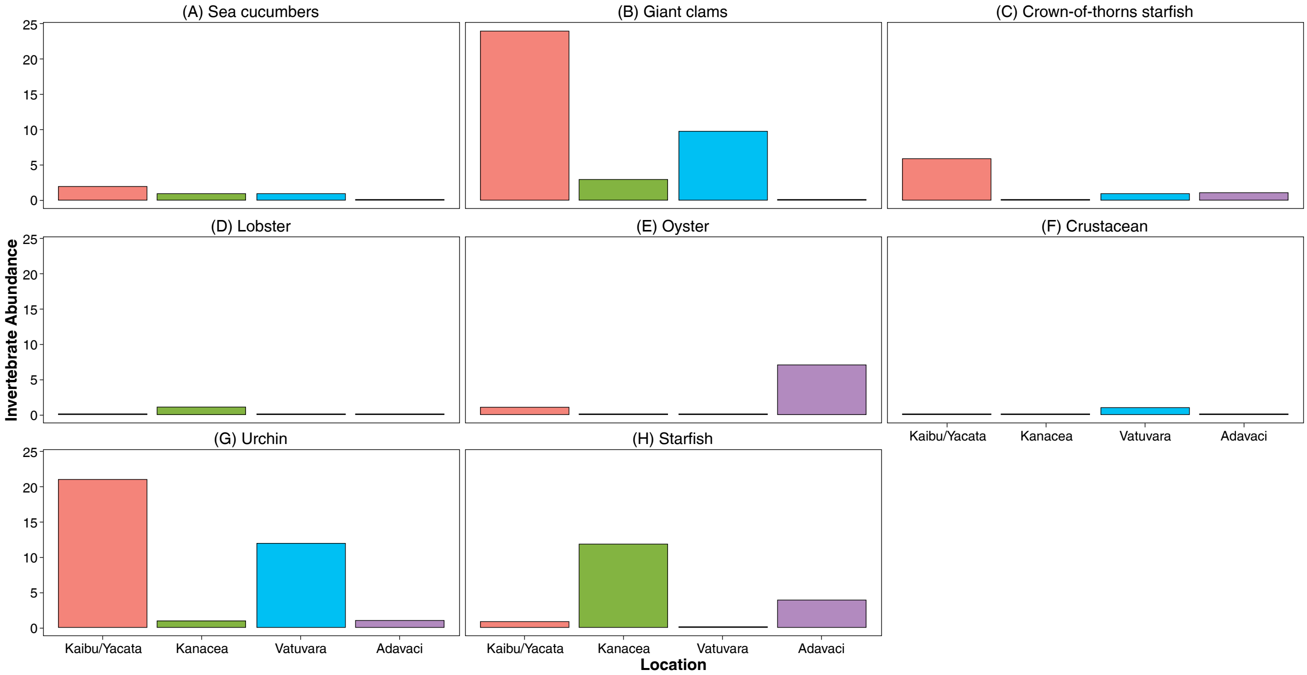

Figure 4. Total abundance of sea cucumbers, giant clams, crown-of-thorns (COTS), lobsters, oysters, crustaceans,urchins and other starfish across the islands.

Yacata and Kaibu islands are within a single barrier reef system with a shallow, sandy lagoon between the islands, and channels connected to the open ocean. @Vatuvara Foundation

Plate 5. Sea cucumber species recorded in the Northern Lau Group in 2017. Species left to right are *Stichopus herrmanni*, *Actinopyga* sp., *Actinopyga mauritiana* and *Pearsonothuria graeffei*. @Sangeeta Mangubhai/WCS

Plate 6. Coral predators *Acanthaster planci* (left) and *Culcita novaeguineae* (right) observed during surveys in the Northern Lau Group. ©Sangeeta Mangubhai/WCS

3.5 Water temperature and quality

Seawater temperature loggers were deployed at 7 sites to monitor sea surface temperature trends (Table 2). Physical parameters were measured for a general assessment of the water quality around each island to establish a baseline for regular monitoring and impact on marine habitats.

The seawater samples indicated pH levels ranged between 8.2–8.4 and salinity content between 40–43 ppt (Table 6). Water quality, based on the Hydrogen Sulphide test (WHO, 2002), calibrated against quantitative laboratory tests (Skyes, 2013) for presence/absence of coliform bacteria was clean. The estimated bacterial content at each site was less than 10 coliform bacteria per 100 ml, which is considerably below the median bacterial content required for primary water contact activities of 150 faecal coliform organisms per 100 ml under Australian and New Zealand fresh and marine water quality guidelines (ANZECC, 2000). In the Hydrogen Sulphide tests, the length of time taken to develop a black colour is an indicator of the level of bacteria present. Overall, the seawater around the islands contained low to moderate levels of bacteria (Table 6), as water tests took over 24 hours to develop a black colouration (Fig. 5).

Table 6. Physical parameters measured for water quality tested at each island.

Island	Kaibu	Kaibu	Yacata	Yacata	Yacata	Vatuvara	Vatuvara	Kanacea	Adavaci
Site	A	B	C	D	E	F	G	H	I
Tide	falling	falling	falling	high	falling	high	high	high	high
Temperature (°C)	27	27	28	27	29	26	27	28	27
Salinity[2]	42	42	42	42	40	41	41	43	43
pH	8.3	8.2	8.4	8.4	8.4	8.4	8.2	8.4	8.4
Depth (m)	2	5	4	3	1	2	3	9	9
Bacterial levels	moderate	low	moderate	low	low	low	low	low	moderate

[2]Unusually high salinity results indicate possible equipment error. Further water quality monitoring will be conducted to determine baseline salinity around the islands surveyed in the Northern Lau group.

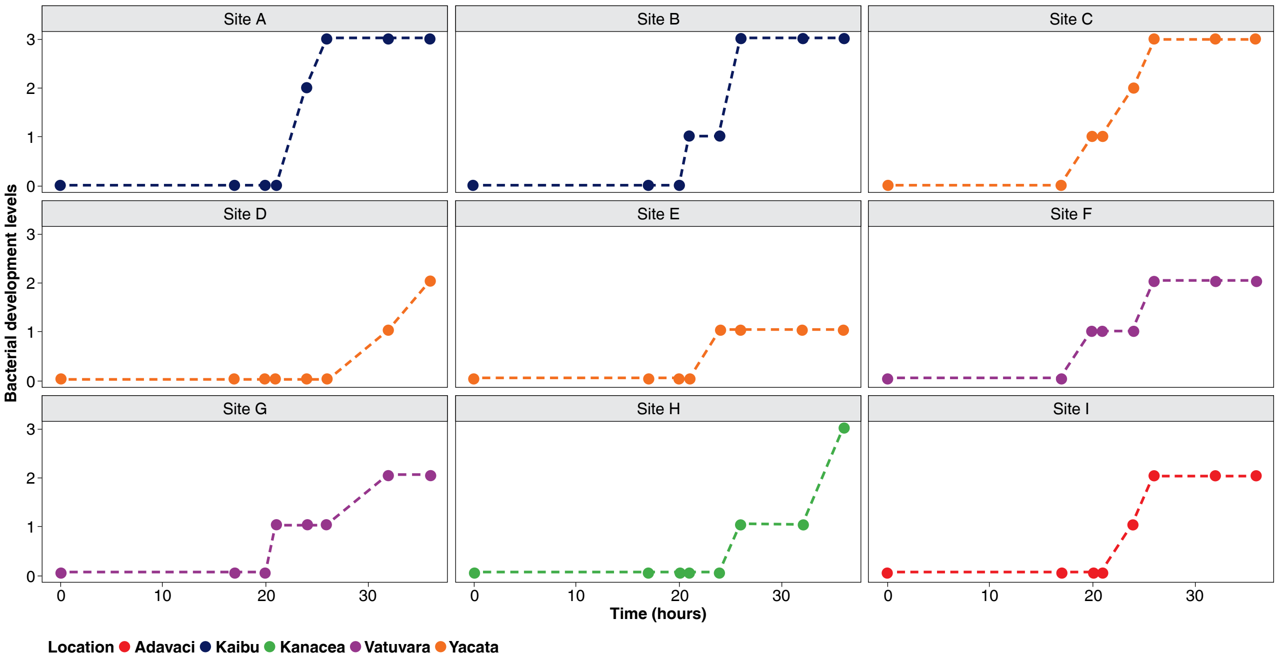

Figure 5. Colour development in the hydrogen sulphide water tests at each site surveyed across the islands. Y-axis represents bacterial development levels denoted on a scale 0–3, where 0=clear water (no bacterial development), 1=water turns light grey (indicating presence of bacteria), 2=water turns dark grey (indicating moderate level of bacteria) and 3=water turns black (indicating high level of bacteria).

4.0 DISCUSSION

This marine biological survey represents the first comprehensive assessment of coral reefs around five islands in the Northern Lau Group. The islands and lagoons of Kaibu, Yacata, and Vatuvara islands were largely healthy, represented a diverse assemblage of hard corals, and are good examples of remote habitats that have not been exposed to intense human pressure. The high currents documented through the lagoon and channels around these islands likely bring in cooler waters, which may aid in buffering sea surface temperature stress. Adavaci and Kanacea islands are located near the larger island of Vanua Balavu which delivers higher land runoff and increased fishing pressure. The low presence of faecal coliform bacteria suggests that there is no land-based pollution, and the waters are clean.[3]

Fiji's coral reefs have shown ability to recover within 5 years after 40–80% mortality from major bleaching events, which is an indication of high resilience (Sykes and Morris, 2007). The average range of coral cover observed during the survey was similar to other healthy reefs in Fiji, that have suffered previous disturbance.The coral damage sustained from Cyclone Winston in Northern Lau suggests that the coral cover could regenerate and recover by 2021 or earlier, if there are no further stresses to the reefs.

The total mean biomass of fishes in the islands (1095 kg ha^{-1}) was similar to other areas in the Lau Province (1126 kg ha^{-1}) (Bruckner et al., 2016) and higher than parts of the Vatu-i-Ra Seascape (Table 1, Mangubhai et al., in press). Fish biomass of 1000 kg ha^{-1} and over are indicative of healthy populations (MacNeil et al., 2015). Populations of commonly targeted fish such as surgeonfish, unicornfish, and parrotfish were relatively abundant; this suggests fishing pressure at these sites was low compared to sites closer to urban centres with populations of herbivores, corallivores and planktivores fairly intact. Fishing around Vatuvara, Kaibu, and Yacata islands is predominantly restricted to subsistence fishing by the local residents explaining the higher fish populations found compared to Adavaci and Kanacea, which are closer to commercial markets (K. Miller, pers. comm.).

A number of globally threatened species were recorded around the islands (Table 7, Plate 7). The humphead wrasse is listed under the Convention on International Trade in Endangered Species of Flora and Fauna (CITES) Appendix II and is considered endangered on the IUCN Red List, and facing a very high risk of extinction (IUCN, 2017). Although sharks were low in numbers, the remote locations of the islands, especially the uninhabited Vatuvara Island, provide some refuge from artisanal and commercial shark fisheries that occur in other parts of Fiji (Glaus et al., 2015). Adult and juvenile humphead wrasses were seen around Vatuvara Island and given the restricted habitat of these fish (Russell, 2004), and their vulnerability to fishing, the reef surrounding Vatuvara Island should be protected.

Blue *Linkia* sea star ©Vatuvara Foundation

Cyclone Winston caused some damage to coral reefs in the Northern Lau Group, particularly at Adavaci which had comparatively low coral cover and higher unconsolidated substrate than the other islands. The cyclone damaged areas had large boulders and upturned corals, high sand and rubble cover, and high algae cover. Corals compete with algae for space and resources, and in extreme disturbances can result in a shift to an algae-dominated system and increase microbial presence (Ainsworth and Mumby, 2014). However, the islands surveyed had higher hard coral cover than algal (turf and assemblages), and healthy fish populations, especially herbivores.

[3]The Australian and New Zealand Guidelines for Fresh and Marine Water Quality recommends water for swimming and other recreational use involving direct skin and water contact should contain less than 150 faecal coliform bacteria per 100 ml (ANZECC, 2000). The coliform bacteria in the seawater sampled at each island was estimated to be lower than 10 faecal coliform bacteria per 100 ml.

Table 7. Marine species of conservation interest seen on coral reefs in the Northern Lau Group that are on the IUCN Red List of Threatened Species (IUCN, 2017).

Common Name	Scientific Name	Conservation Status
Hawksbill turtle	*Eretmochelys imbricata*	Critically Endangered
Green turtle	*Chelonia mydas*	Endangered
Humphead wrasse	*Cheilinus undulatus*	Endangered
White-tip reef shark	*Triaenodon obesus*	Near Threatened
Black-tip reef shark	*Carcharhinus melanopterus*	Near Threatened
Grey reef shark	*Carcharhinus amblyrhynchos*	Near Threatened
Great hammerhead shark	*Sphyrna mokarran*	Endangered
Giant clams	*Tridacna derasa, T. squamosa, T. crocea, T. maxima*	Vulnerable


Plate 7. Threatened white-tip reef shark (*Triaenodon obesus)* (left) and Endangered humphead wrasse *(Cheilinus undulatus)* (right) recorded during the surveys in Northern Lau. ©Helen Sykes/Marine Ecology Consulting

It is difficult to predict how long sites damaged by Cyclone Winston will take to recover as this is dependent on factors including “successful reproduction, availability of viable larvae, oceanic current dynamics influencing larval dispersal, and settlement and recruitment processes” (Mangubhai, 2016). Maintaining healthy populations of herbivorous fish (e.g. surgeonfish, unicornfish, damselfish and parrotfish) are critical to the resilience of coral reef systems, as this functional group reduces algae coverage and removes dead tissue from substrate exposing the underlying reef matrix, which allows for coral recruitment (Dikou, 2010). In many regions, overfishing has caused declines in fish biomass, and the removal of larger herbivorous fish can be linked with various influences on coral degradation and benthic changes of coral reefs (Bonaldo et al., 2017). The ability of these reefs to absorb shocks and resist phase shifts after a disturbance demonstrates the resilience of coral reef ecosystems (Green and Bellwood, 2009). Ecosystems that can maintain their core ecological functions despite a natural disaster are crucial for withstanding future disturbances whether natural or anthropogenic.

Invertebrate populations were notably low. The coral reefs surveyed supported few giant clams, sea cucumbers, crustaceans and urchins. Sea urchins (*Diadema* sp.) play a critical role in maintaining the balance between coral and algae growth (Hernández et al., 2008). Individual crown-of-thorns were observed at certain sites, but there was no evidence of outbreaks. Sea cucumbers are vital to coastal ecosystems, playing a critical role as bioturbators, capable of reducing sediment nutrient loads and microalgal populations by filtering sediments and recycling nutrients (Purcell et al., 2016; Lee, 2016). These species are also an important commercial resource in Fiji that are vulnerable to overexploitation and in the Lau Group there has been large-scale sea cucumber removal over several years (Jupiter et al., 2013; Pakoa et al., 2013; Mangubhai et al., 2017).

Despite the extensive reef area in the lagoons around Vatuvara, Kaibu and Yacata islands, the distribution of clams was sparse. Dense populations of giant clams are rare to find in Fiji, and most reefs have low abundances (less than 6 giant clams observed per hour) (Adams, 1988). Each site surveyed took approximately one hour to complete three invertebrate transects (approximately 20 minutes per transect), and results indicated an average of 3.1 giant clams recorded for each hour across the sites. The increased commercialization of the resource has contributed to its exploitation in Fiji (Copland and Lucas, 1988). These findings provide an understanding of the present stock around the islands surveyed, with the highest abundance of giant clams found at Vatuvara Island. Incorporating the establishment of giant clam sanctuaries into management is highly recommended for the purpose of aggregating brood stock and enhancing recruitment of these sedentary marine organisms to regenerate over time (Copland and Lucas, 1988).

This expedition identified several important conservation sites for protection based on the health of coral and fish communities (Table 8). Establishing a network of LMMAs or MPAs in Northern Lau should be a priority, in close partnership with the local community. The baseline information collected provides a biological benchmark useful to understand environmental changes and recovery rates for these unique reef systems.

Sea anemone and clownfish found at Kaibu Island. ©Vatuvara Foundation

Table 8. Significant sites identified for conservation management at Kaibu, Yacata, Vatuvara and Kanacea islands.

Island	Site Name	Significant Pattern	Importance
Vatuvara	Hidden Jewel (VATU02)	Maximum hard coral cover; Healthy and diverse coral communities; Highest recorded fish biomass.	Biodiversity and ecological complexity; Refuge for corals and populations of threatened species.
	Diversity Drop (VATU03)	High hard coral cover; Healthy and diverse coral communities; High fish biomass.	Biodiversity and ecological complexity; Refuge corals and populations of threatened species.
	World Class (VATU04)	High hard coral cover; High fish biomass; Healthy and diverse coral communities; High reef complexity.	Biodiversity and ecological complexity; Refuge for corals and populations of threatened species.
Yacata/Kaibu	Opposite *Tabu* (YAC02)	Windward forereef adjacent to lagoonal reef and *tabu* area.	Increased recruitment and migration of adults into neighboring habitats.
	Yacata Point (YAC06)	High hard coral cover; Healthy and diverse coral communities.	Biodiversity and ecological complexity.
	Kaibu Passage (YAC08)	High fish biomass and abundant marine life; Sheltered reef with strong tidal currents; Channel mouth critical for feeding and spawning events.	Naturally productive habitat; Ecological role in feeding and reproduction; High vulnerability to over-exploitation.
	Turtle Beach (YAC16)	Leeward forereef adjacent to green and hawksbill turtle nesting sites.	Key marine turtle feeding and nesting area.
	Tabu Shallows (YAC17)	Lagoonal habitat in *tabu* area; High algal cover and evidence of stress.	Impact of multiple stressors on coral communities; Ecological connectivity through adjacent habitats.
	Porites Path (YAC18)	Lagoonal habitat in *tabu* area; diverse coral communities.	Important nursery area for juvenile parrotfish; Maintaining diversity, fish stocks and resilience.
Kanacea	Spur and Groove (KAN05)	High coral diversity; Dominance of branching, corymbose, and plating *Acropora*.	Biodiversity and ecological complexity; Refuge for corals and populations of threatened species.
	Coral Cover Point (KAN06)	High coral diversity; Dominance of branching, corymbose, and plating *Acropora*, *Porites*, and *Pocillopora*.	Biodiversity and ecological complexity; Refuge for corals and populations of threatened species.
	Channel (KAN09)	Channel mouth critical for feeding and spawning events.	Ecological role in feeding and reproduction.

5.0 RECOMMENDATIONS

Given the findings of this assessment, the following recommendations are made:

i. Actions should be taken to minimize human-stresses to coral reefs, especially areas that were impacted by Cyclone Winston;

ii. Protection of coral reefs that were undamaged, which may play a critical role in the recovery of adjacent impacted reefs;

iii. Recommendations to communities of key areas for conservation including sites for inclusion in proposed networks of LMMAs or MPAs should be provided. Planning should be done in consultation with communities, respecting the traditional values, needs and aspirations of communities;

iv. Establish MPAs that are easily enforceable and targeting areas that are diverse, unique and provide refuge for threatened species;

v. Livelihood programs for communities should be developed in order to relieve pressures from marine resources and support sustainable futures;

vi. A surveillance and enforcement strategy should be implemented to reduce threats to coral reefs; and

vii. A monitoring program to measure the recovery of coral reefs should be implemented over the next 2–5 years, and ensure it is linked to management actions.

Healthy branching *Acropora* coral found at Kaibu Island. ©Vatuvara Foundation

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APPENDICES

Appendix 1. Site descriptions of the islands surveyed in Northern Lau in 2017.

Kaibu and Yacata Islands

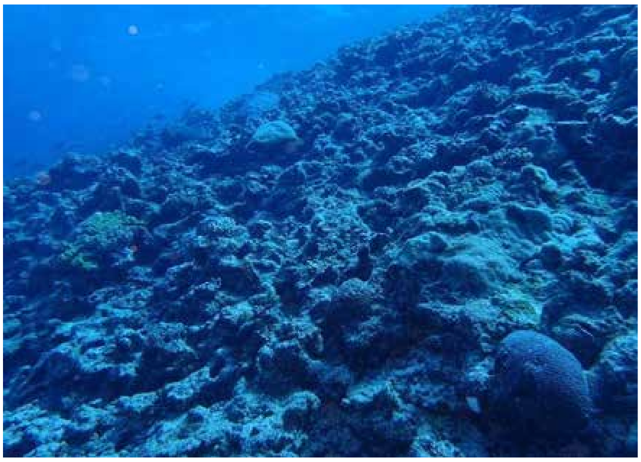
Site #	Site Name	Reef Type	Date
YAC01	Yacata Coral Corner	Leeward Forereef	10 May 2017


The top of the reef started at 5–6 m and sloped gently (20–30°) to a sandy bottom at approximately 18 m. Below 18 m there were more patches of reef on the sandy bottom. The coral community was fairly diverse (left), and was dominated by sub massive and massive *Porites* (right)*;* tabulate, branching, staghorn, and corymbose *Acropora* and faviid species (e.g. *Favia, Favites, Leptoria, Platygyra*). The coral community was healthy and did not show signs of impact from Cyclone Winston. The reef cover was dominated by hard coral (37.0%) and reef matrix (34.0%). Fish biomass averaged 949.5 kg ha^{-1}. This site is suitable for dive visitors, and could be done as a drift dive away from, or towards, the point.

Site #	Site Name	Reef Type	Date
YAC02	Opposite Tabu	Windward Forereef	12 May 2017


This site is opposite the Yacata *tabu* area (YAC18) in the lagoon. The shallow areas between 6–10 m had notable spur and groove structures with large accumulations of boulders at the base, likely from Cyclone Winston. The reef then gently sloped (40°) to 18 m, before it dropped more sharply to a sandy bottom at 25–30 m. The reef cover was dominated by reef matrix (39.3%) and hard corals (34.3%). Fish biomass averaged 964.9 kg ha^{-1}. The site was fairly damaged and had a low coral diversity of mainly submassive and encrusting corals.

Site #	Site Name	Reef Type	Date
YAC03	QereQere	Windward Forereef	12 May 2017



This reef flat sloped at a 50° angle with a few coral patches at a depth of 8–10 m. The slope looked damaged with a large coverage of bare reef substrate with some very complex structure. The slope was dominated by encrusting and some massive and sub-massive coral colonies. The reef cover was dominated by reef matrix (72.0%), hard coral (10.7%) and calcareous algae (9.3%). Fish biomass averaged 1074.9 kg ha^{-1}. This site is suitable for dive visitors, and could be done as a drift dive away or towards the point.

Site #	Site Name	Reef Type	Date
YAC04	Surgeon Slide	Windward Forereef	12 May 2017

This reef flat had very strong surge slopes at an angle of 30°. There were few coral colonies on the slope, where many small fish were counted. Small coral patches were located at a depth 10m. The reef cover was dominated by reef matrix (37.0%), calcareous algae (30.0%) and hard coral (15.3%). Fish biomass averaged 601.9 kg ha^{-1}. This reef system was damaged but the area was covered with available substrate for corals to settle and recover.

Site #	Site Name	Reef Type	Date
YAC05	East Yacata Lagoon	Lagoonal Patch Reef	9 May 2017

This shallow site is within 1 km of the mouth of the channel and experiences strong currents with the rising and falling tides. There were intermittent patches of reefs (left) in between large expanses of sand and rubble. Most of the rubble was well worn suggesting it was many years old. The reef cover was dominated by unconsolidated substrate (58.7%) and microbial (16.3%) and calcareous algae (10.0%). Fish biomass averaged 172.9 kg ha^{-1}. There was a fair amount of microbial mats (green, red, brown) covering rubble and in some places the sand (right). There were some coral recruits on surfaces, but the numbers were low.

Site #	Site Name	Reef Type	Date
YAC06	Yacata Point	Leeward forereef	9 May 2017

The reef started at 6 m and then sloped steeply (70°) to 16 m (left). The reef then sloped gently, with prominent reef outcrops to an unknown depth. Most surfaces were fairly clean, with high cover of pink crustose coralline algae. The reef cover was dominated by reef matrix (49.7%), and hard coral (34.7%). *Porites, Montipora* and *Acropora* species were identified, with encrusting, branching and submassive corals dominating (right). Fish biomass averaged 729.4 kg ha^{-1}.

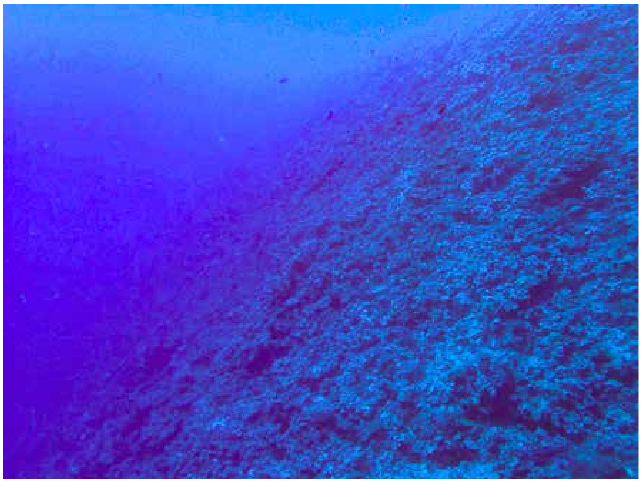
Site #	Site Name	Reef Type	Date
YAC07	Daku's Passage	Leeward Forereef	9 May 2017

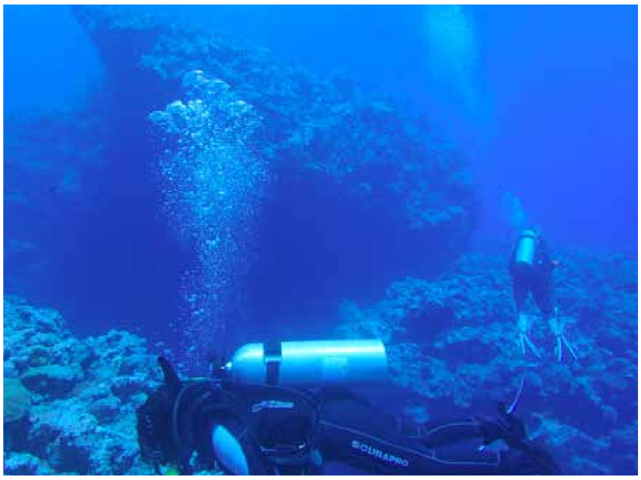
This reef flat had a 50% slope that was dominated by small branching and encrusting corals with a rubble and sandy bottom. The reef cover was dominated by hard coral (33.7%), reef matrix (24.6%) and calcareous algae (19.6%). The site had multiple bommies with similar structures separated by large grooves. All crevices had sandy bottoms with rubble and very low relief. Fish biomass was high, averaging at 1858.4 kg ha^{-1}.

Site #	Site Name	Reef Type	Date
YAC08	Kaibu Passage	Leeward Forereef	9 May 2017

The site was very similar to YAC06, but with a steeper slope (85–90°) to a depth of 17 m (left). The reef then sloped gently, with prominent reef outcrops to an unknown depth. The site was dominated by *Porites, Montipora* and *Acropora* species with encrusting, branching and submassive corals (right). The reef cover was dominated by reef matrix (42.7%), hard coral (20.0%) and calcareous algae (15.6%). Fish biomass averaged 1235.5 kg ha^{-1}. This reef is a suitable recreational dive site.

Site #	Site Name	Reef Type	Date
YAC09	Kaibu Point	Leeward Forereef	9 May 2017



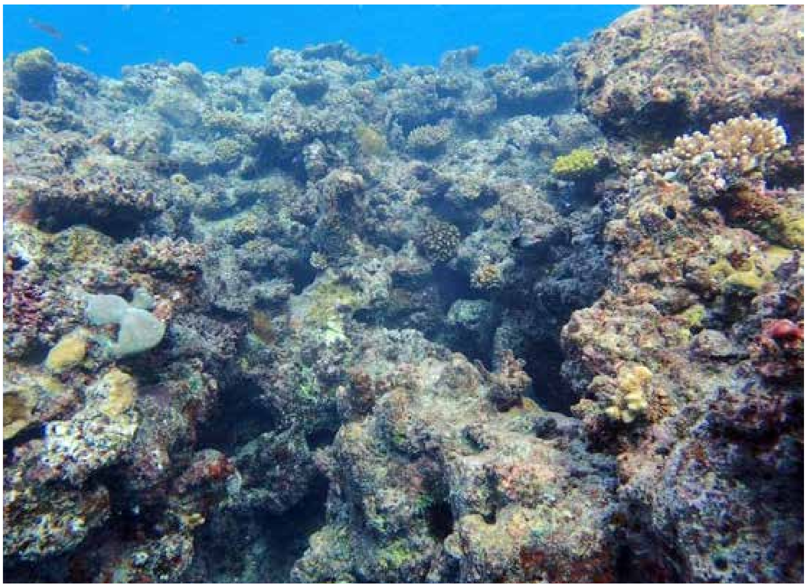


This reef flat had a high surge zone causing a gentle slope at an angle of 110°. Due to exposure to strong wave action and currents, there were medium size corals on the reef that including branching, massive and encrusting growth forms. The reef cover was dominated by reef matrix (45.7%), hard coral (30.0%) and calcareous algae (11.0%). Fish biomass averaged 2667.3kg ha^{-1}, the highest recorded for sites around Kaibu and Yacata islands.

Site #	Site Name	Reef Type	Date
YAC11	GM's Point	Lagoon Patch Reef	9 May 2017

This reef is located within the lagoonal area off Kaibu Island's south western edge. The reef had a large area of continuous reef that gets exposed to high currents and surge, with patches of small bommies. The reef cover was dominated by unconsolidated substrates (32.0%), as there were large areas with sand and rubble between coral bommies. Also dominating reef cover was hard coral (25.0%) and reef matrix (24.6%). Bommies and continuous reefs were dominated by branching and massive colonies. Fish biomass averaged 58.9 kg ha^{-1}.

Site #	Site Name	Reef Type	Date
YAC13	Filo's Passage	Leeward Forereef	8 May 2017

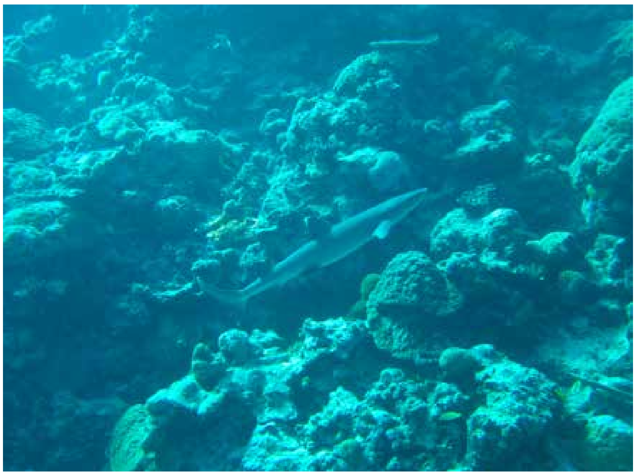


This leeward forereef site was characterized by large bommies (15 m height) on a sandy sloping bottom (left). The tops of the bommies sat 5-6 m below the surface and were largely devoid of coral (right). The sides of the bommies had slopes of 80-90° and were dominated by encrusting corals, particularly *Montipora, Porites* and *Pavona* species. The reef cover was dominated by reef matrix (35.3%), hard coral (19.3%) and unconsolidated substrate (14.6%). The presence of turf, macroalgae and red microbial algae was recorded on surfaces. Fish biomass averaged 1383.9 kg ha^{-1}.

Site #	Site Name	Reef Type	Date
YAC15	Filo's Mooring	Leeward Forereef	9 May 2017

This site had a gentle to steep slope from the reef flat at the angle of 110° to 8 m, followed by a gentle slope to about 20 m. The steep slope from the reef flat was mostly covered with coral patches up to 5 m then was dominated by branching and foliose corals up to 8 m, then patchy corals until 20 m. The reef cover was dominated by hard coral (26.0%), turf algae (21.0%), calcareous algae (18.0%) and microbial (18.3%). Fish biomass averaged 975.5 kg ha^{-1}.

Site #	Site Name	Reef Type	Date
YAC16	Turtle Beach	Leeward Forereef	9 May 2017

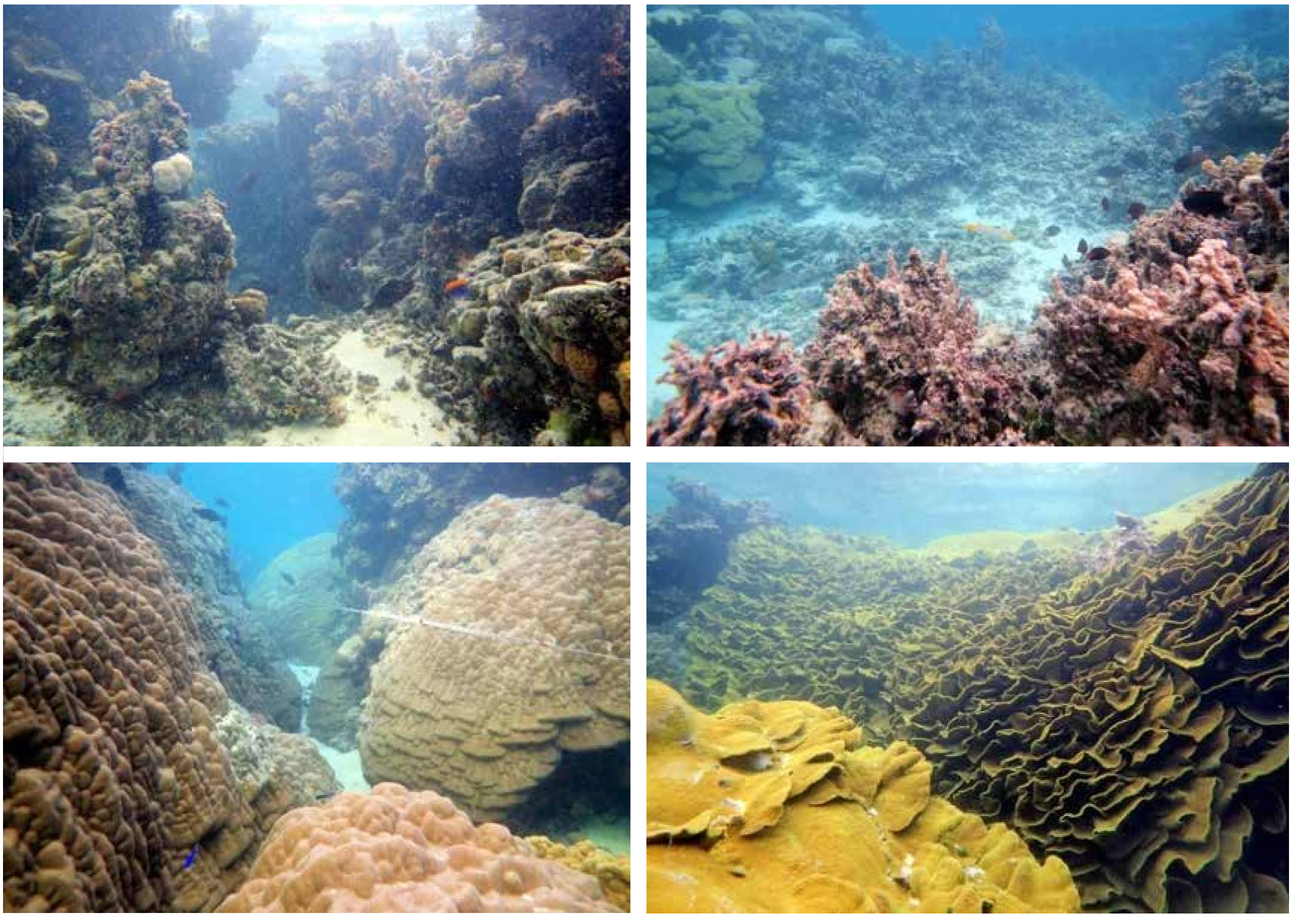



This reef is located close to Yacata's known turtle nesting beach. Reef flat sloped at an angle of approximately 50° in the first 6–8 m. There were small coral patches and bommies separated by sand and rubble. Dominant coral bommines were found at about 15–18 m. Some coral patches were dominated by massive colonies, while others had a combination of massive and sub-massive corals. The reef cover was dominated by hard coral (31.3%), turf algae (23.6%), unconsolidated substrate (11.7%), reef matrix (11.7%) and microbial (11.6%). Fish biomass averaged 978.0 kg ha^{-1}. Two reef sharks were observed during the dive. This reef is potentially a good recreational dive site.

Site #	Site Name	Reef Type	Date
YAC17	Tabu Shallows	Lagoon Patch Reef	11 May 2017


This patch reef is located on the shallow reef flat on the backreef of Yacata Island. This lagoonal habitat was previously a *tabu* area, which was closed to fishing between 2009 to 2013. The reef consisted of a sandy bottom with shallow valleys and coral patch structure. Each coral patch had several crevices, providing shelter for small reef fish. Coral structures were dominated by encrusting and sub-massive colonies. The reef cover was dominated by unconsolidated substrates (45.5%), microbial (32.7%), and turf algae (13.7%). High levels of microalgae cover and dense build-up of microbial on the reef system was recorded. Fish biomass averaged 103.2 kg ha^{-1}.

Site #	Site Name	Reef Type	Date
YAC18	Porities Path	Lagoon Patch Reef	11 May 2017

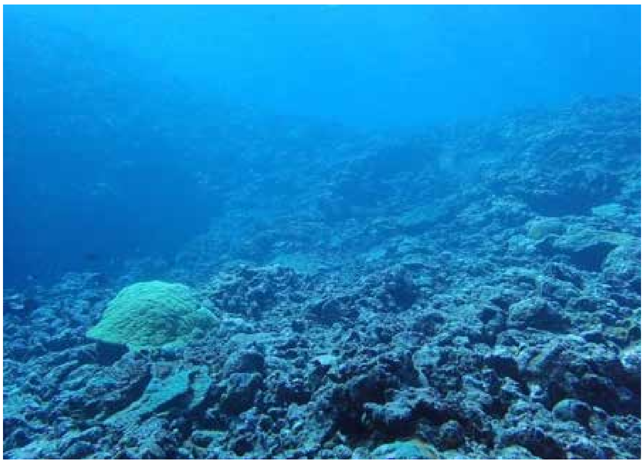


This backreef lagoonal reef is within the previous *tabu* area on the south-western side of Yacata Island. The top of the reef is likely to be exposed on very low tides and had patchy corals sitting in about 2–3 m of water at high tide (top). The reef cover was dominated by unconsolidated substrates (45.0%), hard coral (21.0%), and turf algae (20.0%). Fish biomass averaged 712.7 kg ha^{-1}. Corals were dominated by branching and massive Porites (bottom left) and encrusting corals. There were large stands of branching *Galaxea* and a spectacular formation of yellow *Turbinara* coral (bottom right). Large schools of juvenile parrotfish suggested it was an important nursery area for species.

Site #	Site Name	Reef Type	Date
YAC19	SE Kaibu Point	Windward Forereef	12 May 2015

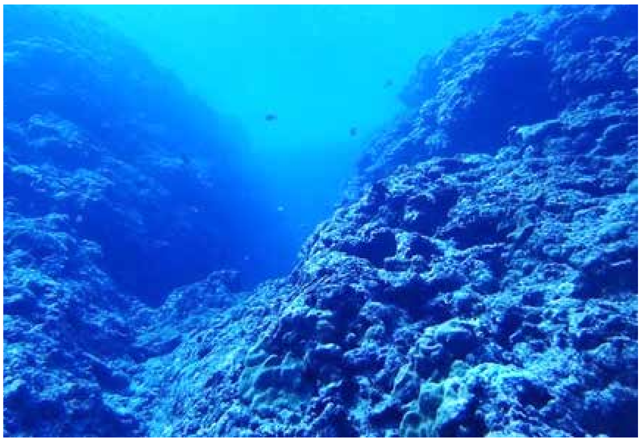
The site is at the most south eastern corner of the reef. The shallow part of the reef started at 5–6 m below the surface and then sloped (45°) to an unknown depth (left). The reef was flat with little relief and large areas of reef matrix. The reef surface was covered with crustose corraline algae, low coral growth and was devoid of fish life (right). The reef cover was dominated by reef matrix (62.3%), hard coral (17.3%), and turf algae (12.6%). Fish biomass averaged 732.5 kg ha^{-1}. This site is not suitable for dive visitors.

Site #	Site Name	Reef Type	Date
YAC20	West Yacata Corner	Windward Forereef	12 May 2015



Despite its proximity to YAC01, there was a marked difference between the leeward and windward sides of the reef that extending out from the point of the island. The windward side started at 5 m, sloped gently (45°) to 18 m, then more sharply (75°) to a sandy bottom at approximately 25 m (left). The reef cover was dominated by hard coral (33.0%), unconsolidated substrate (27.3%) and reef matrix (28.6%). There were large areas of damage from Cyclone Winston with larger boulders piled up in places 6–8 m below the surface and only small patches of healthy reef (right). However, much of the substrate was stable, and young corals (<5 cm) were seen on reef surfaces suggesting recovery had started. Fish biomass averaged 464.4 kg ha^{-1}. This site is not suitable for dive visitors.

Site #	Site Name	Reef Type	Date
YAC21	Tabu Point	Sheltered Windward Forereef	12 May 2017



This sheltered reef slope was angled away from sun at 40°. There were many small fish and a few sharks recorded. Also seen during the dive were trevally, groupers and big snappers. The reef cover was dominated by reef matrix (58.6%), and hard coral (25.6%). The reef slope was mostly dominated with spur and grove reef structures with branching, massive and encrusting coral colonies. Fish biomass averaged 1533.6 kg ha^{-1}.

Vatuvara Island

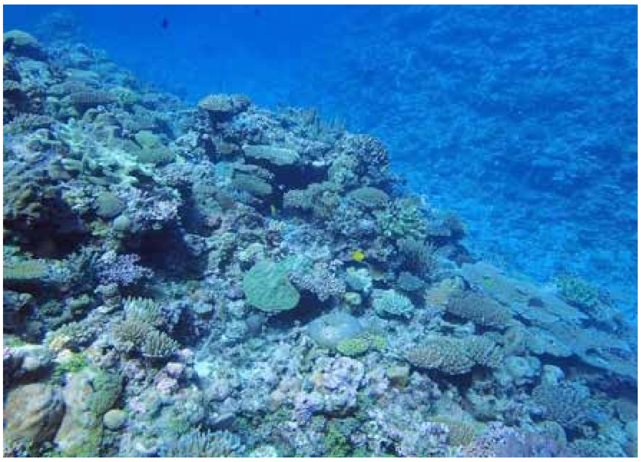
Site #	Site Name	Reef Type	Date
VATU01	Picnic Beach Reef	Lagoon Patch Reef	13 May 2017

This shallow lagoon reef flat is located on the southern side of Vatuvara Island. The back-reef area was 1 m deep, with patches of small coral colonies and continuous reef structure. The reef cover was dominated by reef matrix (48.7%), unconsolidated substrate (25.7%), and hard coral (10.0%). Fish biomass averaged 374.1 kg ha^{-1}. Prominent large *Porites* were observed with micro atoll formations from low tide exposure situated along the site. Some damage to coral was seen.

Site #	Site Name	Reef Type	Date
VATU02	Hidden Jewel	Sheltered Windward Forereef	13 May 2015

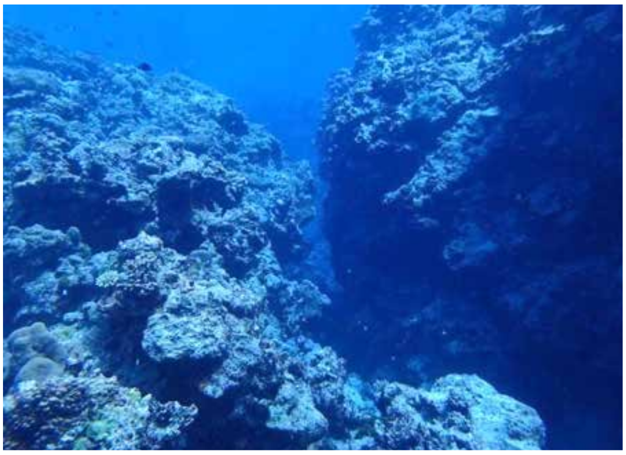

The top of the reef started at 5–6 m depth and the slope dropped fairly continuously (75–80°) to an unknown depth (left). The reef was healthy, with high hard coral cover (48.7%) and diversity dominated by *Acropora* (branching, tabulate, corymbose), *Pocillopora* and *Porites* species (right). Average fish biomass was 5886.9 kg ha^{-1} and the highest recorded across sites surveyed. There were large schools of drummers, parrotfish, fusiliers, and snappers (*Lutjanus gibbus*). Three humphead wrasses were observed, as well as a whitetip reef shark. This site is highly suitable for recreational divers.

Site #	Site Name	Reef Type	Date
VATU03	Diversity Drop	Leeward Forereef	13 May 2015




The reef started at 2-3 m, sloped sharply (60°) to 6 m, and then slopes more gently (45°) to 11 m (left), before the reef dropped more sharply (80°) to an unknown depth. Later the slope became a steep wall (90°). The reef cover was dominated by hard coral (36.0%), calcareous algae (30.3%), and reef matrix (25.7%). The coral community was healthy and diverse, with mainly *Acropora, Porites* and *Pocillopora* species (right). Fish biomass averaged 2242.0 kg ha^{-1}. This site is suitable for recreational divers.

Site #	Site Name	Reef Type	Date
VATU04	Worldclass	Leeward Forereef	13 May 2017




This reef sloped at an angle of 70°, which eventually droping into a steep wall containing swim through structures and large crevices. The site was characterized by large spur and groove structures. A number of massive and plate corals were sighted with a few rare coral genera such as *Oxypora, Mycedium, Echinopyllia*. The reef cover was dominated by hard coral (33.7%) and reef matrix (33.7%). Fish biomass averaged 2894.2 kg ha^{-1}. There were a few very curious white tip reef sharks, and sleeping sharks were observed in the deeper crevices. This is a “worldclass” dive site for recreational divers.

Site #	Site Name	Reef Type	Date
VATU05	Windward Beach	Windward Forereef	13 May 2017

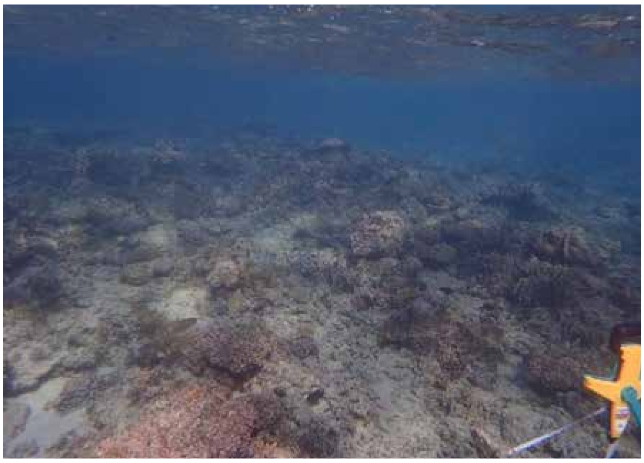

This reef angled at 30° into a complex structure with curves forming a shallow cradle at 10 m. The beginning of the reef had large massive and sub massive coral colonies. At around 50 m, the reef was damaged with overturned corals. This reef had low coral cover and turf algae was evident. The reef cover was dominated by reef matrix (66.3%) and hard coral (20.3%). Fish biomass averaged 999.9 kg ha^{-1}. Although, this windward reef experiences harsh conditions due to wind and surge exposure, the reef system was quite complex with various large fish counted.

Site #	Site Name	Reef Type	Date
VATU06	Picnic Beach Drop Off	Sheltered Windward Forereef	13 May 2015


The top of the reef started at 5 m, and then sloped (60°) to 10 m, before sloping again (30–40°) to 18 m. The deeper reef dropped more sharply (70°) to a sandier bottom with patch reefs. The reef had little relief and little coral (mostly species of *Porites* and *faviids*) (left). Towards the shallows there were large areas of rubble and boulders, suggesting the site was highly impacted by Cyclone Winston (right). The reef cover was dominated by reef matrix (28.3%), turf algae (26.7%) and unconsolidated substrate (22.7%). Fish biomass averaged 629.2 kg ha^{-1}. The presence of small corals (<5 cm) on bare substrate suggest recovery had started. This site is not suitable for dive visitors.

Kanacea Island

Site #	Site Name	Reef Type	Date
KAN03	Blue Sea Star Lane	Lagoon Patch Reef	14 May 2017



This lagoonal patch reef is located on the northern side of Kanacea Island. The reef cover was dominated by reef matrix (52.0%), hard coral (18.7%), unconsolidated substrate (8.0%), and algal assemblage (6.0%). Fish biomass averaged 322.4 kg ha^{-1}. The reef had a gentle slope covered in dead coral, with evident algae and macro algae cover. The majority of the reef was dominated by sand and rubble. Blue *Linkia* sea stars were found in large numbers along the reef top.

Site #	Site Name	Reef Type	Date
KAN04	Outer Reef Point	Windward Forereef	15 May 2017

This reef flat drops to about 10 m then slopes at an angle of 45–50°. The reef slope had a complex and intact reef structure, however, there were clear signs of the damage on the reef. A large number of overturned corals and pieces of broken reef structure were observed. The reef cover was dominated by reef matrix (41.7%) and unconsolidated substrate (38.0%). The reef slope had various intact coral patches that were very intact, indicating a high recovery potential. The visibility was beyond 15 m and large numbers of fish were recorded in the area. Fish biomass averaged 1441.8 kg ha^{-1}.

Site #	Site Name	Reef Type	Date
KAN05	Spur and Groove	Leeward Forereef	15 May 2017




The site was characterized by large spur and groove structures. The spurs were covered in corals (top) and the groves were largely sand and rubble. The reef cover was dominated by hard coral (42.0%) and reef matrix (24.0%). There was a high diversity of corals, with *Acropora* (branching, corymbose, plating) dominating the site (bottom). The shallows started at 5–6 m, and sloped gently (45°) to 16 m, before sloping more steeply to the bottom of the reef. Fish biomass averaged 581.8 kg ha^{-1}. There were large numbers of fusiliers and parrotfish at the site. There were frequent sightings of green and hawksbill turtles. This is a suitable site for recreational divers.

Site #	Site Name	Reef Type	Date
KAN06	Coral Cover Point	Leeward Forereef	15 May 2017




The site was characterized by large spur and groove structures, with spurs covered in corals and the grooves largely of sand and rubble. The top of the reef was covered in 7–8 m of water, and sloped gently (50–60°) until around 12 m, then more sharply (80–90°) to an unknown depth. There were also large bommies or pinnacles at 7-8 m height on sandy slopes. The reef cover was dominated by hard coral (44.0%), with high coral diversity of *Acropora* (branching, corymbose, plating), *Porites*, and *Pocillopora.* Average fish biomass was 1632.3 kg ha^{-1}. There were frequent sightings of green and hawksbill turtles, and a giant hammerhead shark. This is a suitable site for recreational divers.

Site #	Site Name	Reef Type	Date
KAN07	Pinnacle Point	Leeward Forereef	14 May 2017

This reef flat had a shallow drop-off with macro structures that create a complex reef system. The reef cover was dominated by reef matrix (37.7%) and hard coral (20.0%). The coral patches had shallow valleys consisting of sand and rubble. The reef was mostly dominated by massive, branching and foliose corals. Damage to areas of the reef was observed. Average fish biomass was 383.9 kg ha^{-1}. There was poor visibility during the survey dive, which made recording fish difficult. There were several shallow pinnacles within close distance to this forereef system.

Site #	Site Name	Reef Type	Date
KAN08	Kanacea Entrance	Leeward Forereef	14 May 2017

This site is located outside and to the right of the main channel entrance to the lagoon of Kanacea Island. The reef was shallow (<5 m) with the reef wall at 85–90° (left). The reefs are fairly poor and degraded with low coral cover (right). The reef cover was dominated by unconsolidated substrate (35.0%) and hard coral (17.6%). The base of the reef was largely sand and rubble, and evident microbial algae over reefs and rubble surfaces. This site is not suitable for dive visitors.

Site #	Site Name	Reef Type	Date
KAN09	Channel	Lagoon Patch Reef	14 May 2017


This reef site was a small channel in from the Northern forereef. The top of the reef is about 30–40 cm below the surface and was dominated by branching, corymbose and short table *Acropora* (left). The reef cover was dominated by reef matrix (40.3%) and hard coral (34.3%). The density and diversity of corals appeared highest closest to the outer reef, and decreased within the lagoon. The channel bottom was largely sand with small bommies and *Porites* (right). This is a suitable site for guest snorkellers.

Adavaci Island

Site #	Site Name	Reef Type	Date
ADA01	Patchy Shallows	Patch Reef	15 May 2017


This site was relatively degraded (left), with patchy reefs on a shallow slope (30–40°) and largely sand and rubble substrate (right). The reef levelled out around 14 m. The reef cover was dominated by unconsolidated substrate (77.7%) and microbial (9.0%). Coral and fish abundance was low compared to other sites surveyed. Average fish biomass was 349.3 kg ha^{-1}. There were a few large stands of branching *Porites* and *Pavona clavus,* but there was a high cover of microbial algae on sand and reef surfaces.

Site #	Site Name	Reef Type	Date
ADA04	Outer Main Beach	Windward Forereef	15 May 2017

This shallow reef site had very poor visibility. The reef flat sloped at an angle of about 20° to a shallow sandy bottom. The reef cover was dominated by unconsolidated substrate (58.6%) and reef matrix (13.6%). There were clear signs of damage from the cyclone, as large number of coral heads (coral patches) were ripped off the shallow reef flats areas. A large number of huge branching and massive corals were overturned. Although heads of *Porites* were still intact, there was a high percentage of macro, turf and calcareous algae sighted on the reef. Average fish biomass was 338.0 kg ha^{-1}.

Appendix 2. Coral genera present (x) around islands surveyed in 2017.

GENERA	Kaibu_Yacata	Vatuvara	Adavaci	Kanacea
Acanthastrea	x	x	x	x
Acropora	x	x	x	x
Astreopora	x	x		x
Caulastrea				x
Coscinaraea	x	x	x	x
Ctenactis			x	x
Cyphastrea	x	x	x	x
Diploastrea	x	x	x	x
Echinophyllia	x	x	x	x
Echinopora	x	x	x	x
Favia	x	x		x
Favites	x	x	x	x
Fungia	x	x	x	x
Galaxea	x	x		x
Gardinoseris	x	x		
Goniastrea	x	x		x
Goniopora			x	x
Herpolitha	x	x	x	x
Hydnophora	x	x		x
Isopora	x	x		x
Leptastrea	x	x	x	x
Leptoria	x	x		x
Leptoseris	x			x
Lobophyllia	x	x	x	x
Merulina	x	x	x	x
Millepora		x	x	x
Montastrea	x	x		x
Montipora	x	x	x	x
Mycedium		x		x
Oulophyllia	x	x		x
Oxypora	x			x
Pachyseris			x	x
Pavona	x	x	x	x
Pectinia			x	
Platygyra	x	x	x	x
Pocillopora	x	x	x	x
Podobacia	x			
Polyphyllia	x	x	x	
Porites	x	x	x	x
Psammacora	x			x
Sandolitha	x	x	x	
Scolymia	x			x
Seriatopora	x	x		x
Stylophora	x	x	x	x
Symphyllia	x	x	x	x
Tubastrea		x		
Turbinaria	x	x	x	x
TOTAL GENERA	39	37	28	41

Appendix 3. Fish families present and total number of fish species recorded around islands surveyed in 2017.

Family	Kaibu_Yacata	Vatuvara	Adavaci	Kanacea
Acanthuridae	26	27	11	15
Aulostomidae	1			
Apogonidae			1	
Balistidae	10	8	2	6
Blenniidae	4	1	2	1
Caesionidae	6	5	1	6
Carangidae	5	3		2
Carcharhinidae	2	2	1	1
Chaetodontiae	27	21	11	25
Chanidae	1			
Cirrhitidae	2			
Echeneidae & Malacanthidae	1			
Ephippidae	1			1
Gobiidae	1	2	1	2
Haemullidae	2	3	2	2
Holocentridae	5	3		2
Kyphosidae	2	2		
Labridae	43	35	18	33
Lethrinidae	7	6	3	6
Lutjanidae	11	8	3	9
Microdesmidae	3	1	2	3
Mullidae	10	11	5	10
Nemipteridae	1	1	1	2
Ostraciidae	1			
Pinguipedidae		1	1	1
Pomacanthidae	6	5	2	6
Pomacentridae	31	26	12	19
Priacanthidae				1
Scaridae	19	19	9	15
Scombridae	1			1
Scorpaenidae			1	1
Serranidae	13	7	4	7
Siganidae	4	2	1	5
Sphyrnidae				1
Sphyraenidae		1		
Tetradonitidae	2		2	1
Zanclidae	1	1		1
TOTAL SPECIES	249	201	96	185

This expedition identified several important conservation areas for protection.

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