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Assessment of Multiple Citizen Science Methods and Carbon Footprint of Tourists in Two Australian Marine Parks

Adam K. Smith [1,2,*], Joseph D. DiBattista [3], Samatha J. Tol [2], Leona Kustra [4], Joanne Stacey [1], Toni Massey [5] and Paul E. Hardisty [6]

[1] Reef Ecologic, 14 Cleveland Terrace, Townsville, QLD 4810, Australia; joanne.stacey@reefecologic.org
[2] Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER), James Cook University, Cairns, QLD 4878, Australia; samantha.tol@jcu.edu.au
[3] School of Environment and Science, Griffith University, Southport, QLD 4222, Australia; j.dibattista@griffith.edu.au
[4] Coral Conservation Society, 15372 Victoria Ave., White Rock, BC V4B 1H2, Canada; leonakustra@gmail.com
[5] Cultural Heritage Management Australia, 4/8 Hampden Rd., Battery Point, TAS 7004, Australia; toni@chma.com.au
[6] P38 Media and Consulting, 12a Myera St., Swanbourne, WA 6010, Australia; paulehardisty@gmail.com
* Correspondence: adam.smith@reefecologic.org

Abstract: Citizen or community science (CS) projects in the marine environment rarely consider carbon footprint and sustainability. In this case study, we assessed the effectiveness of ten CS methods used by tourists in the Great Barrier Reef Marine Park (GBRMP) and Coral Sea Marine Park (CSMP) who participated in the 2023 Citizen Science of the Great Barrier Reef expedition and the carbon footprint associated with these field methods. We also assessed the baseline coral reef knowledge of the tourists, observations of marine species, and the communication of our results to the public. Specifically, the tourists utilised up to ten methods: iNaturalist, CoralWatch, Great Barrier Reef Census, Eye on the Reef (EoR), environmental DNA (eDNA) testing kits, photogrammetry, social surveys, and Red Map, as well as marine debris and marine vegetation collections. A total of 10,421 data points were collected across 14 days, including 5390 records (52% of the total) uploaded to iNaturalist, comprising 640 plant and animal species. Public awareness of the CS expedition reached over 700,000 people based on estimates from advertising, media, social media, family and friends, and conference presentations. We estimated the total carbon footprint for the expedition as 268.7 tonnes of CO_2 or 4.47 tonnes of CO_2 per person, equivalent to AUD 112 needed to offset this input. Based on these results, our recommendations to leverage CS methods include governmental review strategies, temporal replication to allow for the measurement of changes through time, integrating sustainability into CS ecotourism platforms, and encouraging broad participation.

Keywords: carbon footprint; coral; Coral Sea; fish; Great Barrier Reef; environmental DNA; iNaturalist

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Citation: Smith, A.K.; DiBattista, J.D.; Tol, S.J.; Kustra, L.; Stacey, J.; Massey, T.; Hardisty, P.E. Assessment of Multiple Citizen Science Methods and Carbon Footprint of Tourists in Two Australian Marine Parks. *Sustainability* **2024**, *16*, 11019. https://doi.org/10.3390/su162411019

Academic Editors: Wei Jiang and George P. Kraemer

Received: 29 October 2024
Revised: 30 November 2024
Accepted: 11 December 2024
Published: 16 December 2024

1. Introduction

Citizen science (CS) is the engagement of the public as volunteers in a scientific project alongside scientists. Such collaborations can improve the quantity and reach of data collections at little additional cost to the project. These projects can range from small-scale research focused on a single species [1,2] to large-scale research of multiple species with both spatial and temporal components [3,4]. These potential benefits can also integrate more broadly into the social sciences [5]. Citizen science projects that deliver high data density per location, wide geographic coverage, or regular observations over time are considered particularly valuable [6]. Citizens can participate in every stage of the project, from problem identification to experimental design, data collection, data analysis, and dissemination of the results [7–9]. One of the important aspects of CS is that it engages members of the public in science and in the places and issues the science is designed to support. Given the current stresses faced by coral reefs worldwide, the benefits of citizen science are more important than ever before in tropical ecosystems.

The number of CS projects has increased worldwide over the last decade as public interest in the environment grows and as technology allows more people to engage meaningfully in data collection, particularly in the natural environment [10]. As a result, science and management organisations, tourism companies, and expedition charters have increasingly started to incorporate citizen science into their activities [10–12]. However, marine CS participation has been lower than that for terrestrial systems [13,14], likely because of the challenges associated with field logistics, accessibility, equipment (or lack thereof), training, safety, and culture [8,15].

There are currently over 134 CS programmes operating in Queensland, Australia, and they are either run by management authorities, tourism operators, researchers, dive enthusiasts, or members of the general public [15–19]. An online survey of 1145 marine end users reported that most citizen scientists tended to have a degree in science, were under 45 years old, enjoyed SCUBA diving, and had contributed to scientific research in the past [10].

It is standard practice to focus on one CS methodology per project [15,20]; however, an increasing number of projects are employing multiple methods to enable a broader perspective and integrate these data sources [21]. Combining multiple CS tools not only increases the scope of data collected but can improve the probability of overall success in case one or more methods fall short of expectations. This is particularly valuable when data collection sites are remote and difficult to access.

1.1. Great Barrier Reef and Coral Sea

The Great Barrier Reef is a complex marine ecosystem, protected within the 344,400 km^2 Great Barrier Reef Marine Park (GBRMP), set along the north-eastern coast of Australia. Directly offshore and adjacent to the GBRMP is the Coral Sea Marine Park (CSMP), covering an even greater area of 989,836 km^2, making it the largest of Australia’s marine parks [22]. Both marine parks are considered biodiversity hotspots [22,23] and managed by state and federal government agencies in Australia. Although the GBRMP has attracted significant research effort and funding over the last century, research in the CSMP has been comparatively limited due to its remote location, situated at least 200 km from the Australian mainland [24].

1.2. Carbon Footprint

A carbon footprint (or greenhouse gas footprint) is a calculated value or index that makes it possible to compare the total amount of greenhouse gases that an activity, product, company, or country adds to the atmosphere. There are several methodologies and online tools to calculate the carbon footprint, but most of them measure one type of impact, e.g., flight, car, boat. These methodologies depend on whether the focus is on a country, organisation, product, or individual person [25]. Tourism is responsible for 8–10% and citizen science is responsible for less than 1% of the of the world’s carbon emissions. Current research on the field of tourism and citizen science carbon emissions rarely describes the research dilemmas and future trends that the field desperately needs to address [25,26].

The tourism company Coral Expeditions and the media company Australian Geographic have developed a series of annual expeditions with a programme of scientific, cultural, historic, and nature-based activities facilitated by expert staff and guest lecturers [27]. The 2023 expedition promoted as the ‘Citizen Science of the Great Barrier Reef expedition’ [28], the subject of this paper, had five aims: (1) Coral Expeditions passengers and staff learn about reef species, management and science (and underwater cultural heritage), (2) Coral Expeditions passengers and staff are scientific partners, actively involved in scientific endeavours to generate new knowledge or understanding about the Great Barrier Reef and Coral Sea, (3) CS projects deliver a genuine scientific outcome, including expanding our knowledge of species distribution and in select cases abundance, and disseminating that knowledge through reports and scientific papers, (4) the expedition communicates with the general public and the scientific community through diverse channels, including art, video, web, news, and social media, and (5) fundraising is organised to support a carbon-neutral expedition.

2. Materials and Methods

The research and ecotourism vessel *Coral Discoverer* departed from Cairns on 23 October 2023 and returned 14 days later on 6 November 2023. Six scientists and guest lecturers provided training in multiple CS methods to 40 guests. Guest lecturers and guests collected CS data during visits to 12 different islands, cays, and reefs in the Great Barrier Reef Marine Park (9 locations) and Coral Sea Marine Park (3 locations) (Figure 1).

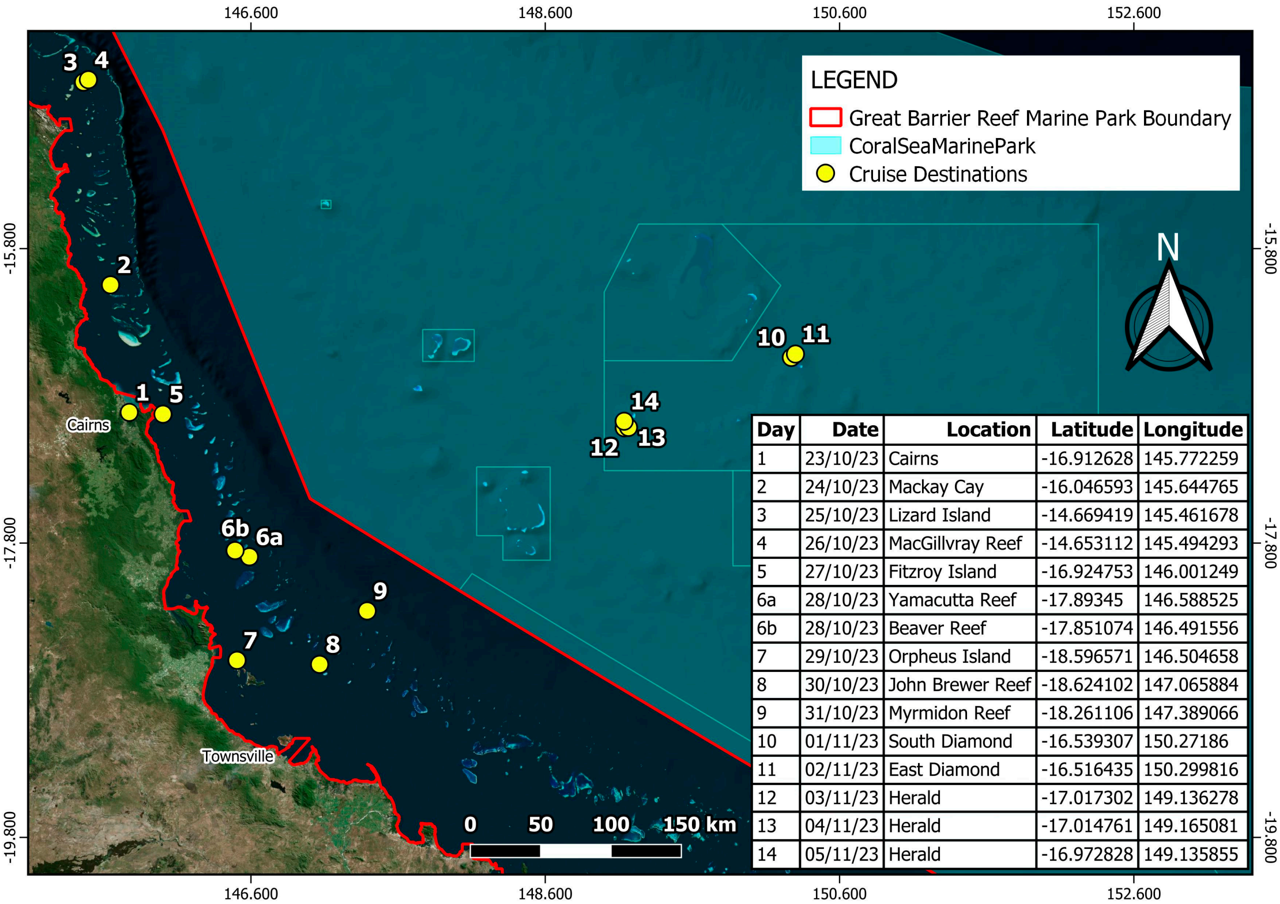

Figure 1. Map of sampling locations and sites (days) and the boundaries of the Great Barrier Reef Marine Park and Coral Sea Marine Park.

A pre-expedition research plan with daily communication (lectures, newsletter, workshop, meetings, art) and field activities focused on four types of CS tools: biodiversity audits, reef health checks, heritage assessments, and social surveys, including ten specific CS tools [29] that were made available based on guest training, location, experience, and interest (Table 1). We included an activity for artists to be involved in an expedition sketchbook to complement knowledge sharing, communication, and learning.

Table 1. Four citizen science (CS) assessment methods based on biodiversity audits, reef health checks, heritage assessments, and social surveys, including ten individual CS tools used during the expedition.

Methods	Tools
Biodiversity audit	iNaturalist, eDNA, algae collection
Reef health check	Coral Watch, GBR Census, Eye on the Reef, Red Map, marine debris
Heritage assessment	Photogrammetry
Social survey	Questionnaire

2.1. Biodiversity Audit Tools

Sampling was conducted by scientists and snorkel and SCUBA divers at water depths of 1–20 m, generally associated with reef lagoon habitats.

2.1.1. iNaturalist Tool

Initiated in 2011, iNaturalist (www.inaturalist.org, accessed on 14 December 2023) is a multi-taxa platform that allows participants to contribute observations of any organism or traces thereof, along with associated spatiotemporal metadata, to a centralised website. Observations are initially identified by the user or with the assistance of artificial intelligence computer vision suggestions and then identified and verified to high taxonomic resolution by the iNaturalist community. An observation is deemed 'Research Grade' when it meets the site's metadata quality criteria and has two or more suggested identifications, more than two-thirds of which agree at a species level [30].

The iNaturalist project 'Citizen science of the Great Barrier Reef and Coral Sea' [31] was created with a focus on marine biota and spatial and temporal boundaries. Observers were restricted to the citizen scientists on the expedition. Identifiers were not restricted. *t*-tests were used to compare data between the GBRMP and CSMP.

2.1.2. eDNA Tool

Water samples were collected at four sites (N = 4 replicates at each) in the GBRMP and CSMP between 29 October 2023, and 4 November 2023, to provide a complementary whole-ecosystem biodiversity detection dataset. For each water replicate, a sterile eDNA syringe mini kit containing a 30 mm $\times$ 1.2 µm cellulose acetate syringe filter with a Luer-lock inlet and outlet fitting was used (Wilderlab NZ Ltd., Wellington, New Zealand). The target water filtration volume was 2.5 L. Post-filtration, syringe filters were preserved with 350 µL of DNA/RNA Shield (Zymo Research Cat. No. R1200-125). Protocols followed [32–34]. More detail is provided in Supplementary S1.

2.1.3. Marine Vegetation Collection Tool

Seagrass and algal specimens were targeted for collection to assist in the creation of a marine vegetation library for both marine reserves. Marine vegetation specimens vouchered in state and federal herbariums are severely lacking for the GBRMP and absent for the CSMP. These specimens will provide visual libraries, as well as a source of genetic tissues, if requested by other researchers. All specimens collected were pat-dried with a paper towel before being placed in an herbarium press between multiple pieces of newspaper. Newspapers were replaced daily to ensure specimens did not stick to the paper, until the specimen was completely dry. Data on location, date, species, and collector's name were recorded in an herbarium data book, along with descriptions of location and number of specimens.

2.2. Reef Health Check Tools

2.2.1. CoralWatch Tool

Initiated in 2002 as a scientific research effort, CoralWatch is a global CS programme that integrates education and global reef monitoring to examine coral bleaching. CoralWatch data have been collected in over 80 countries and from 2245 different reefs. The main tool that CoralWatch participants use is the Coral Health Chart, which records changes in coral colour and represents a simple tool for citizens to monitor coral health. Records of coral colour changes over time provide data on coral health changes at the individual reef scale (Figure 2; [35]). We used the online CoralWatch analysis tool (https://coralwatch.org/monitoring/analyse-your-data/, accessed on 14 December 2023) to summarise our survey data. These data were visualised using a bar graph for coral colour scores, where a healthy reef generally scores 3 or more. We used a pie chart to show the percentages of the four coral types (Boulder, Branching, Plate, Soft), and a *t*-test was used to compare the coral bleaching data between the GBRMP and CSMP. Statistics were run in R version 4.3.1 (R Core Team 2023, https://www.R-project.org/, accessed on 14 December 2023), with a measure of significance when $\alpha < 0.05$.

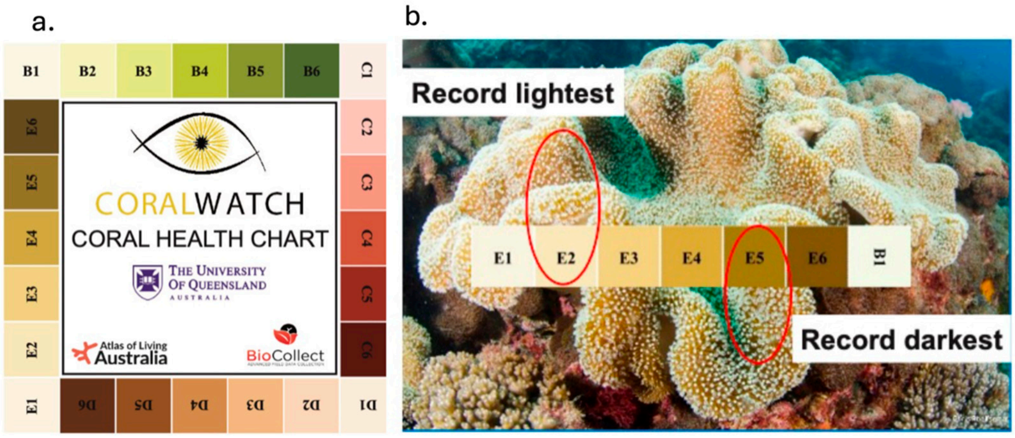

Figure 2. (**a**) The Coral Health Chart records changes in coral colour. (**b**) Demonstration of the two data measurements by citizen scientists record the lightest (E2) and darkest (E5) area within one coral colony. From Coral Watch (2021) Health Chart Do it Yourself instructions.

2.2.2. Great Barrier Reef Census Tool

Initiated in 2020, the Great Reef Census is an annual CS effort to survey the Great Barrier Reef between 1 October and 31 January, and so our expedition fell within this sampling window. The Great Reef Census collects tens of thousands of photos from hundreds of reefs across the GBR. An individual survey is made of up to 40 representative photos from a reef site, with each image capturing at least 5 × 5 m of a reefscape edge [36]. These images are uploaded to an online platform, where people from across the world identify the types of coral and the extent of coral cover per site [36].

2.2.3. Eye on the Reef Tool

Initiated in 2007 by the Great Barrier Reef Marine Park Authority, the Eye on the Reef programme aims to provide a multi-tiered approach to reef health monitoring and assessment. It is designed for people with little to moderate reef experience who can either snorkel confidently or SCUBA dive. The tiers we used were embedded within the Reef Health Impact Survey (RHIS), which assesses reef health in a series of five metre radius circles (a total of 78.5 m^2), and the Rapid Monitoring Survey, which involves a 10 min timed swim and count of 18 categories of animals: sea cucumber, giant clam, anemonefish, butterflyfish, grazing herbivores, cods and groupers, coral trout (×2), Maori wrasse (×2), turtle (×3), shark (×3), and crown-of-thorns starfish (×2) [20]. A GLM, with a negative binomial distribution to adjust for over-dispersion, was used to compare the data between the GBRMP and CSMP. Statistics were run in R version 4.3.1, with a measure of significance when $p < 0.05$.

2.2.4. Redmap Tool

Initiated in 2009, Redmap (Range Extension Database and Mapping Project) is an online tool that invites Australians to share sightings of marine species that are uncommon or rare to their local area. The data collected aim to highlight areas and species that may be experiencing range expansion owing to environmental change so that future research may be focused in these areas. In Queensland waters, there are currently fifteen species of fish, four mammals, one reptile, and five sharks and rays that are the focus of this research, although additional species may be logged and reviewed [37].

2.2.5. Marine Debris Tool

The Australian Marine Debris Initiative (AMDI) is run by the Tangaroa Blue Foundation and provides a scalable, collaborative framework to address marine debris impacting Australia from both domestic and international sources. Organised beach clean-ups and litter surveys are popular with volunteers. Community clean-up surveys provide data on the amount and different types of debris found, as well as hotspots where it is accumulating. Our intention in the use of this tool was to determine whether there might be hotpots in the GBRMP and CSMP where debris was notable or accumulating.

2.3. Heritage Tool

Photogrammetry

Photogrammetry involves taking overlapping photographs of an object, structure, or space and converting them into 2D or 3D digital models [38]. From these models, accurate measurements of an object, reef or shipwreck can be made. Our intention in its use was to apply this tool to a historical shipwreck on a CSMP reef.

2.4. Social Survey Tool

Questionnaire

Social surveys were conducted on four occasions (twice in the GBRMP and twice in the CSMP) between 29 October and 5 November 2023 by intercept interviews or by a self-administered online questionnaire (Supplementary S2). Survey metrics were categorised into four broad themes: knowledge of the reef, health of the reef, satisfaction with the trip, and CS. A total of 16 questions (Supplementary S2) were provided and included tick box and words for simplicity, as well as five- to ten-point Likert-type scales for statistical rigour. The surveys were completed by participants within 3 to 5 min. We used a multiple linear regression model to test whether the perceived health of the reef and information received from CS significantly affected the satisfaction level of visitors to the CSMP and GBRMP. The model used was specified by $Y = \beta0 + \beta1X1 + \beta2X2$, where X1 is the health and X2 is the information received. This analysis of survey data aimed to provide an understanding of how these variables affected satisfaction levels. Statistical analysis was performed in R version 4.3.1, with a measure of significance when $\alpha < 0.05$.

2.5. Carbon Footprint Tool

An integrated tool to calculate plane, vessel, and car travel for the complete footprint of the expedition was not available. We instead included seven separate inputs for fuel use and greenhouse gas calculations: large vessel, medium vessel, small vessel, generator, international flights, domestic flights, and car travel. We measured distance and fuel use for the large vessel and estimated fuel use for medium and smaller vessels, using a multiplication factor of 2.68 [39] to convert to greenhouse gas tonnes. We estimated the number of international and domestic passengers, as well as the staff on board, and applied an average for flight times to and from Cairns. We noted that established integrated tools assume ¼ tonne CO_2 equivalent per passenger per hour flying [40]. We therefore assumed an average of two hours for domestic staff and passengers, as well as 25 h for international passengers. We assumed one tonne of greenhouse gas emissions for every 1000 km of car travel. We noted that the average cost of an eligible carbon offset in Australia was AUD 25 per tonne of CO_2 abated.

3. Results

A summary of the dates and locations visited during the expedition, as well as the type and number of CS data collected, is provided in Table 2.

Table 2. Comparison of the number of observations/surveys for selected CS tools, as well as notes on results for other tools. Key: GBRMP—Great Barrier Reef Marine Park; CSMP—Coral Sea Marine Park; iNat—iNaturalist; EoR—Eye on the Reef; D—eDNA; R—Redmap; S—social.

Location	Site	Date	Methods				
			iNat	Coral Watch	GBR Census	EoR	Other
GBRMP	Mackay Cay	24/10/23	345	0	1	0	0
	Lizard Island	25/10/23	616	105	1	0	0
	MacGillvray Reef	26/10/23	508	20	1	0	0
	Fitzroy Island	27/10/23	170	0	1	0	0
	Yamacutta Reef	28/10/23	170	0	1	0	0
	Orpheus Island	29/10/23	253	0	1	0	4D, 32S
	John Brewer Reef	30/10/23	419	45	2	7	4D, 22S, 1R
	Myrmidon Reef	31/10/23	275	70	0	5	0
CSMP	South Diamond Islet	01/11/23	149	0	0	6	4D
	East Diamond Islet	02/11/23	353	0	0	2	15S
	North Herald Cay	03/11/23	348	101	0	0	3S
	South Herald Cay	04/11/23	409	37	0	2	4D, 15S
	South Herald Cay	05/11/23	454	0	0	0	20S
	Totals		4478	381	8	22	16D, 1R, 106S

3.1. Biodiversity Audit Results

3.1.1. iNaturalist

In total, 5390 CS observations (individual data entries) were downloaded from the expedition iNaturalist project. These observations were made by twenty-five people, with the top five observers recording 74% of all observations. A total of 10,660 identifications (species identifications by other users) were made by 188 people, with the top 5 people recording 41% of all identifications. There were, on average, 7.9 ± 0.4 research-grade observations per species (median = 4 records per species), ranging from a single observation for 44% of the species observed to 85 observations for *Acropora* spp. (Elkhorn and Staghorn corals). Several species were recorded for the first time in the GBRMP and CSMP using iNaturalist, including Eightband Butterflyfish (*Chaetodon octofasciatus*), Sixspot Glidergoby (*Valenciennea sexguttata*), Bluehead Tilefish (*Hoplolatilus starcki*), Curious Wormfish (*Gunnellichthys curiosus*), and Pimpled Basket Sea Snail (*Nassarius papillosus*). A total of 268 species (47%) were uniquely observed in the GBRMP and 137 species (24%) were uniquely observed in the CSMP; 165 species (29%) were observed in both marine parks (Figure 3).

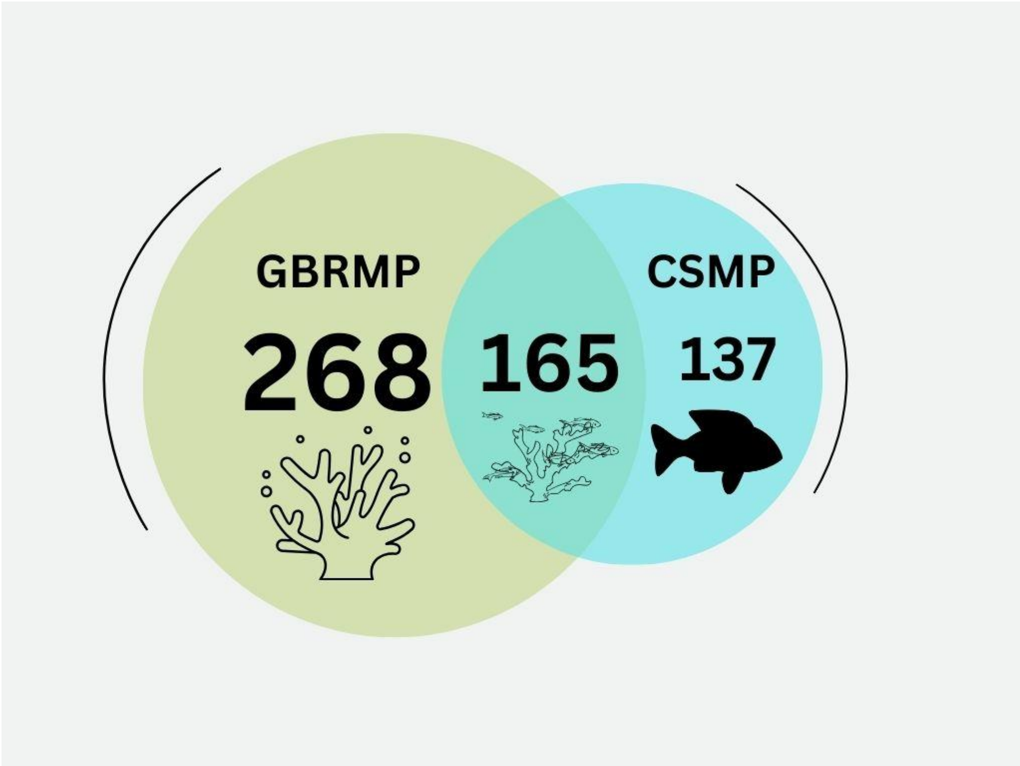

Figure 3. Comparison of the number of species uniquely observed in the Great Barrier Reef Marine Park (GBRMP) and the Coral Sea Marine Park (CSMP), as well as those common to both areas.

Of the 5390 observations, 85% (4586) were identified to species, of which 98% (4478) were categorised as 'Research Grade', thus contributing 570 species (Table 3). The largest proportion and diversity of observations were ray-finned fishes (78.4%, 391 species), followed by molluscs (5.8%, 58 species), corals (4.7%, 56 species), and sea cucumbers (3.0%, 14 species). The remaining 8% of observations were made up of birds (2.2%, 4 species), sharks (1.2%, 7 species), crustaceans (1.1%, 11 species), sea turtles (1.0%, green sea turtle or *Chelonia mydas* only), sea stars (0.9%, 7 species), algae (0.8%, 11 species), ascidians (0.4%, 2 species), sponges (0.1%, 3 species), hydrozoans (0.1%, 2 species), and terrestrial plants (0.1%, 3 species) (Figure 4a,b).

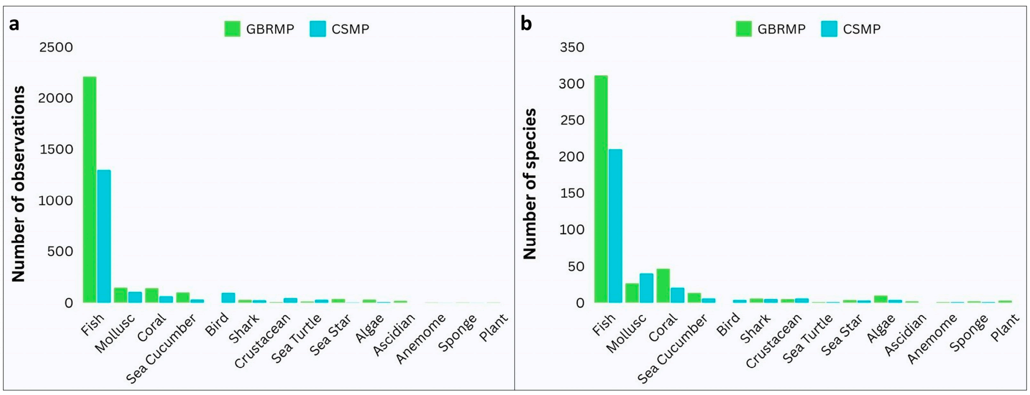

Figure 4. (**a**) The number of observations per taxa and the (**b**) number of species observed per taxa on the iNaturalist app during the citizen science survey of the Great Barrier Reef Marine Park (GBRMP) and Coral Sea Marine Park (CSMP).

Table 3. Top five observed species of fish, molluscs, and other taxa in each of the Great Barrier Reef Marine Park (GBRMP) and Coral Sea Marine Park (CSMP) based on the number of iNaturalist observations exported on 28 January 2024.

Scientific Name	Common Name	GBRMP	CSMP
Ray-Finned Fishes			
Naso unicornis	Bluespine Unicornfish		34
Paracirrhites arcatus	Ringeye Hawkfish		32
Zanclus cornutus	Moorish Idol		31
Lutjanus bohar	Two-spot Red Snapper		29
Naso lituratus	Pacific Orange-spine Unicornfish		29
Scarus frenatus	Sixband Parrotfish	45	
Scolopsis bilineata	Two-line Monocle Bream	43	
Acanthochromis polyacanthus	Spiny Puller	40	
Siganus doliatus	Blue Lined Rabbitfish	38	
Abudefduf sexfasciatus	Scissortail Sergeant	36	
Molluscs			
Tridacna gigas	Gigas Giant Clam	58	
Tridacna crocea	Boring Giant Clam	30	
Tridacna spp.	Giant Clams	12	16
Tridacna derasa	Smooth Giant Clam	10	7
Tridacna maxima	Small Giant Clam	7	14
Lambis truncata	Giant Spider Conch		19
Hippopus hippopus	Bear Paw Clam		8
Other Taxa			
Acropora spp.	Table, Elkhorn, and Staghorn Corals	85	
Linckia laevigata	Blue Linckia	28	
Lobophyllia spp.	Open Brain Corals	28	
Sarcophyton spp.	Toadstool Leather Corals	27	
Bohadschia argus	Leopard Sea Cucumber	22	
Coenobita perlatus	Strawberry Hermit Crab		33
Sula dactylatra	Masked Booby		32
Sula sula	Red-footed Booby		30
Chelonia mydas	Green Sea Turtle		29
Sula leucogaster	Brown Booby		21

There was no difference in the number of observations between the two marine parks (GLM: $t.ratio_{13} = -0.834$, $\alpha = 0.4193$); however, there were significantly more observations of ray-finned fish compared to anemones (GLM: $t.ratio_{13} = -4.770$, $\alpha = 0.0151$), ascidians (GLM: $t.ratio_{13} = -4.507$, $\alpha = 0.0232$), sponges (GLM: $t.ratio_{13} = 4.770$, $\alpha = 0.0151$), and terrestrial plants (GLM: $t.ratio_{13} = 5.033$, $\alpha = 0.0098$). There was no difference in the number of species per taxa observed between the two marine parks (GLM: $t.ratio_{13} = -1.397$; $\alpha = 0.1859$); however, there were significantly more species of ray-finned fish observed compared to all other taxa, except molluscs and corals (GLM: $\alpha = 0.0016$). There were also significantly more molluscs and coral species observed than the other taxonomic subgroups (i.e., birds, sea turtles, ascidians, anemones, sponges, and terrestrial plants; GLM: $\alpha < 0.001$)

The top five observed species of fish and all other taxa for the GBRMP and CSMP are listed in Table 3.

3.1.2. eDNA

In total, 7507 amplicon sequence variants (ASVs) were generated in the full dataset (i.e., all ASVs considered in each assay independently) through bioinformatic processing. Once ASVs were aggregated across all assays, our dataset included 876 unique taxa, of which 787 taxa were associated with aquatic environments. Based on the aggregated dataset, 193 (22.0%) of our DNA sequences were identified as fish, 153 (17.5%) as bacteria, and 90 (10.3%) as plants; all other taxonomic groups ranged between 7.1% and <1% (Figure 5).

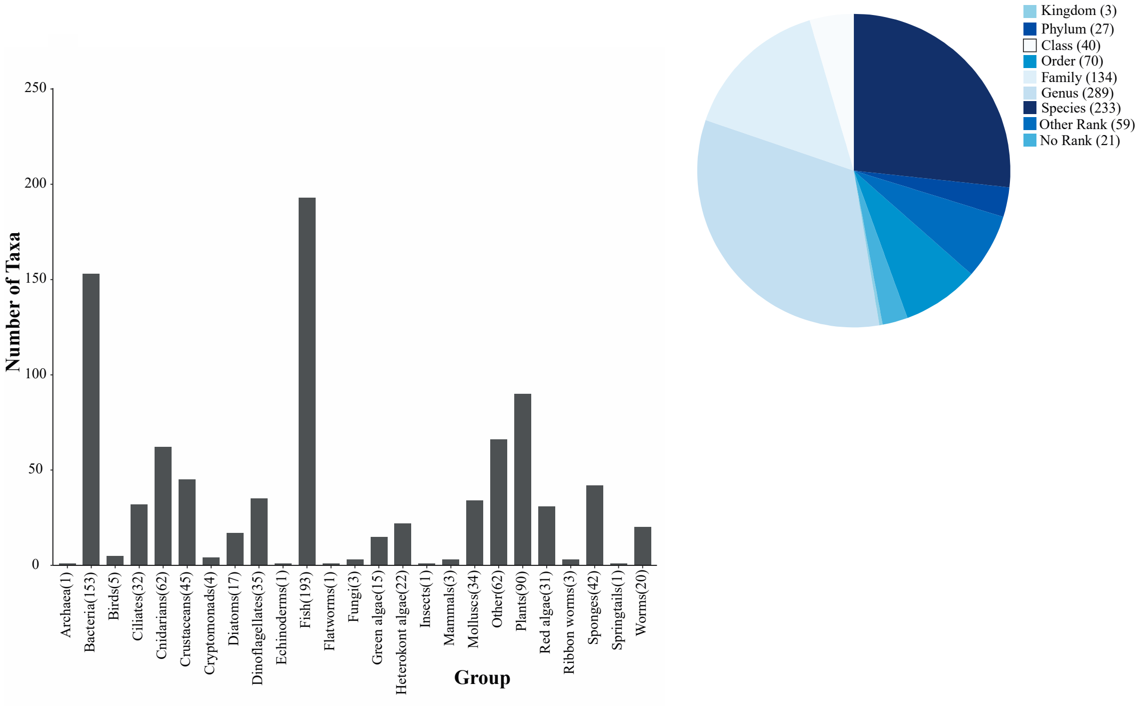

Figure 5. The number of unique DNA sequences (i.e., Amplified Sequence Variants or ASVs) in the aggregated environmental DNA (eDNA) dataset (N = 876) as a function of taxonomic group and accompanying pie chart displaying the taxonomic rank of those assignments. Numbers in parentheses represent the number of taxa in all cases. 'Other' taxonomic ranks included those designated a clade, isolate, tribe, varietas, subspecies, subfamily, superfamily, suborder, subclass, infraclass, or superkingdom.

Phylogenetic trees based on the ASVs illustrated the relationship between the taxonomic groups and taxa recorded independently in the GBRMP and CSMP (Supplementary Material S3) based on seawater samples collected at two locations and four replicates per location (N = 8 for GBRMP and N = 8 for CSMP).

3.1.3. Marine Vegetation Collection

A total of nineteen algal specimens and one seagrass herbarium specimen were collected on the expedition, comprising fifteen algal samples from six islands and reefs in the GBRMP and four algal samples and one seagrass sample from the Herald Cays in the CSMP (Table 4).

Table 4. Algal and seagrass specimens collected in late 2023 in the Great Barrier Reef Marine Park (GBRMP) and Coral Sea Marine Park (CSMP) for an herbarium collection.

Location	Site	Date	Taxa	Species	Qty
GBRMP	Mackay Reef	24/10/2023	Brown algae	*Padina* spp.	1
	Mackay Reef	24/10/2023	Red algae	*Laurencia* spp.	1
	Lizard Island	25/10/2023	Brown algae	*Padina* spp.	1
	Fitzroy Island	27/10/2023	Green algae	*Caulerpa nummularia*	1
	Fitzroy Island	27/10/2023	Green algae	*Halimeda* spp.	1
	Fitzroy Island	27/10/2023	Red algae	*Yamadella* spp.	1
	Beaver Reef	28/10/2023	Red algae	*Laurencia snackeyi*	1
	Beaver Reef	28/10/2023	Red algae	*Titanophycus* spp.	1
	Beaver Reef	28/10/2023	Red algae	*Laurencia dendroidea*	1
	Beaver Reef	28/10/2023	Green algae	*Caulerpa cupressoides*	1
	Beaver Reef	28/10/2023	Green algae	*Halimeda* spp.	1
	Orpheus Island	29/10/2023	Brown algae	*Padina* spp.	1
	John Brewer Reef	30/10/2023	Brown algae	*Sargassopsis decurrens*	3
	John Brewer Reef	30/10/2023	Red algae	*Asparagopsis taxiformis*	1
	Mackay Reef	24/10/2023	Green algae	*Halimeda* spp.	1
CSMP	North Herald Cay	02/11/2023	Seagrass	*Halophila decipiens*	2
	North Herald Cay	02/11/2023	Green algae	*Halimeda* spp.	1
	North Herald Cay	02/11/2023	Green algae	*Avrainvillea calathina*	2
	South Herald Cay	04/11/2023	Green algae	*Halimeda* spp.	1
	South Herald Cay	04/11/2023	Green algae	*Caulerpa cupressoides*	2

3.2. Reef Health Check Results

3.2.1. CoralWatch

A comparison of the 239 coral surveys from the GBRMP and 138 coral surveys from the CSMP found that, on average, both marine reserves had slightly more corals scoring below a healthy score of 3 (GBRMP average = 2.9 ± 0.06, with 55% scoring less than 3; CSMP = average 2.7 ± 0.07, with 58% scoring less than 3) (Figure 6a,b). Coral health was significantly worse in the CSMP compared to the GBRMP, based on CoralWatch data (*t*-test: $t = 2.2399$, $df = 321.34$, $\alpha = 0.03$). The morphology of corals was evenly split across the four main categories for the GBR (branching = 17.1%, plate = 32.6%, boulder = 29.1%, and soft = 21.2%), whereas the CSMP had nearly equal branching (49.5%) and boulder (37.6%) corals, fewer soft corals (11.9%), and almost no plate corals (1%) recorded (Figure 6c,d).

3.2.2. Great Barrier Reef Census

We collected 184 photos across six coral reefs in the GBRMP over seven separate surveys (two reefs were surveyed twice). The data were submitted online to the Great Barrier Reef census website (https://greatreefcensus.org/, accessed on 14 December 2023). As of the date of publication, the data have not yet been analysed and are not publicly available.

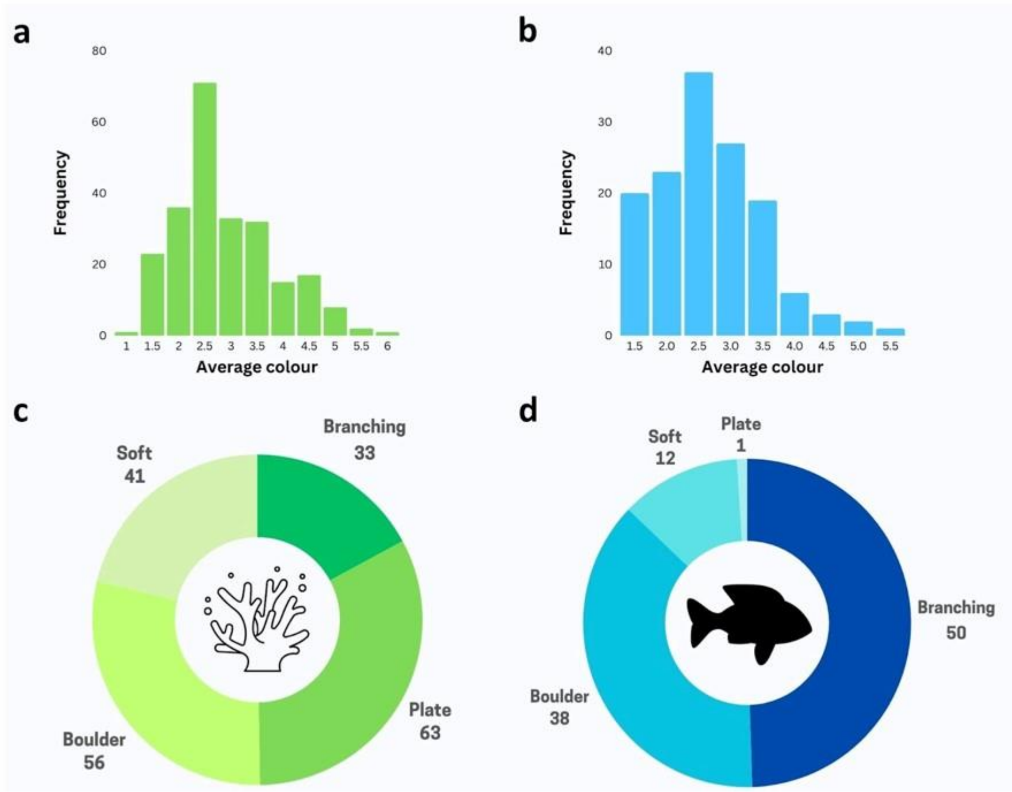

Figure 6. Average coral colour distribution in the (**a**) Great Barrier Reef Marine Park (GBRMP) and the (**b**) Coral Sea Marine Park (CSMP), as well as coral morphology in the (**c**) GBRMP and (**d**) CSMP.

3.2.3. Eye on the Reef

We conducted a total of 22 surveys and recorded 2518 biota from 18 categories. The most abundant categories were grazing herbivores (47%), butterflyfish (34%), and sea cucumbers (11%). No data were recorded for five categories: green turtle, hawksbill turtle, other turtle, blacktip shark, and crown-of-thorns starfish (Figure 7).

The primary differences in biota between the two regions were the greater number of sea cucumbers observed in the GBRMP (GLM.nb: Z.ratio = -5.838, $\alpha < 0.001$) and lesser number of butterflyfish (GLM.nb: Z.ratio = 4.170, $\alpha = 0.0145$). Although there was a trend for more giant clams in the GBRMP, this was not statistically different (GLM.nb: Z.ratio = -3.709, $\alpha = 0.0770$) (Figure 7).

3.2.4. Marine Debris

Multiple full garbage bags of marine debris were collected either floating on the water's surface or washed up on the beach of sand cays and islands in both marine parks. Some notable items were multiple intact fluorescent 3 ft light bulbs on South Herald Cay in the CSMP. Unfortunately, due to a lack of interest among the passengers and time to process the haul, we did not weigh or collate data on the marine debris collected.

3.3. Heritage Assessment Results

Photographs along a 50 m transect were processed to create a summary of the coral habitats and remnants of the historic shipwreck *Foam*, which wrecked on Myrmidon Reef in 1893. A previously unknown anchor was recorded during the survey and reported to the Queensland Department of Environment, Science and Innovation (DESI), as well as the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

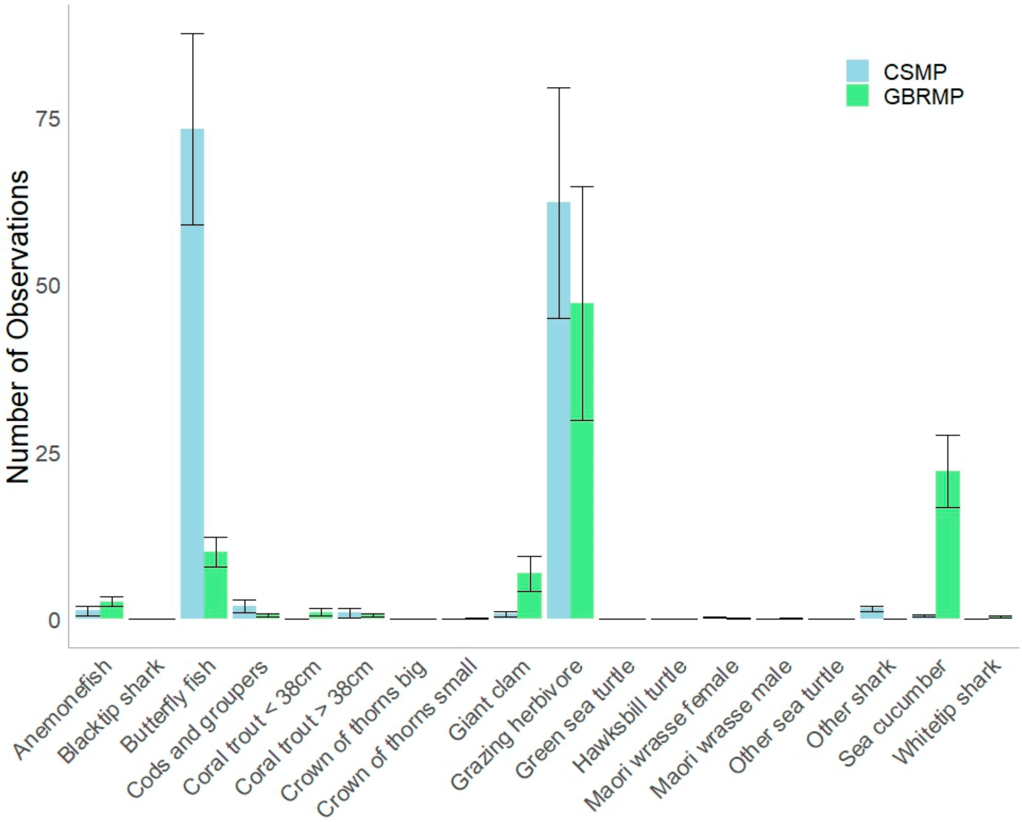

Figure 7. Observations within 18 categories of animals using the Eye on the Reef survey methodology (i.e., rapid, 10 min surveys) from the Great Barrier Reef Marine Park (GBRMP—green) and Coral Sea Marine Park (CSMP—blue).

3.4. Social Survey Results

Questionnaire

A total of 106 surveys were completed by citizen scientists; 53 were completed within our expedition time in the GBRMP and 53 were completed within our expedition time in the CSMP. We collated all data for survey participants related to their knowledge of coral reefs. The majority (64%) of citizen scientists reported that they had a low knowledge of coral reefs and self-identified as novices (scores 1 to 4). A small percentage (12%) of citizen scientists reported that they had a high knowledge of coral reefs and considered themselves experts (scores 8 to 10).

In response to the survey question 'What CS tools did you use today?', the participants used between 0 (19%) and 4 (3.9%) CS tools, averaging 1.22 CS tools per day. The most frequently used CS tool in both the GBRMP and CSMP was iNaturalist (52.7%; Figure 8), followed by Coral Watch (16.3%) and GBR Census (10.9%). No survey respondents reported using RedMap during the survey (Figure 8).

A majority (89%) of the participants reported high levels of satisfaction (scores 8 to 10) in response to a question about their overall satisfaction with the day's activities (Figure 9). We found no significant difference between levels of satisfaction for trips in the CSMP versus the GBRMP. The model used as specified by $Y = \beta0 + \beta1X1 + \beta2X2$, where X1 is the health condition and X2 is the information received, aimed to provide an understanding of how these variables affect satisfaction levels. The model's overall fit was statistically significant ($F_{2,101} = 22.62$, $\alpha < 0.001$), suggesting that the model explained a significant portion of the variance in satisfaction levels. The adjusted R^2 value of 0.2957 illustrated that our model accounted for approximately 30% of the satisfaction level variability, highlighting the included predictors' impact. It was found that both health and information ($\beta = 0.124$, $\alpha < 0.001$) significantly predicted satisfaction levels.

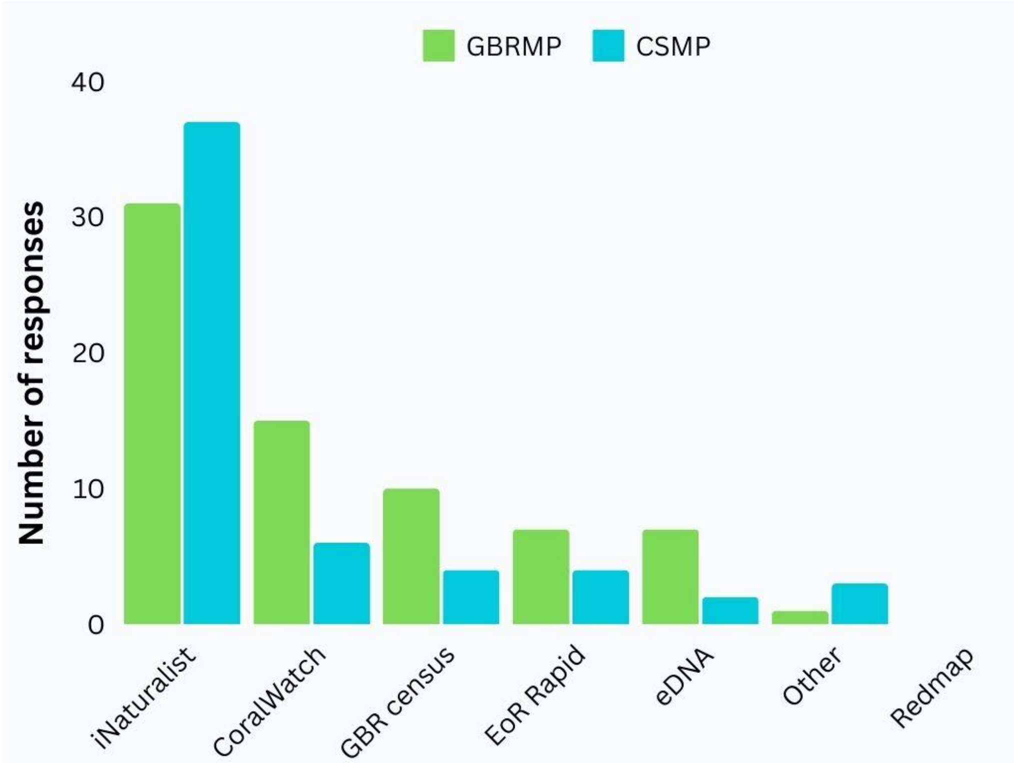

Figure 8. Response to survey question 'What citizen science tools did you use today?' when compared between the Great Barrier Reef Marine Park (GBRMP) and Coral Sea Marine Park (CSMP) (N = 129).

A direct quote from one of the tourists who rated the quality of the information delivered as 9/10 stated, 'I'd just like to comment on the excellent standard of education, general manner and interpersonal skills of the group leaders. I'm happy such people are leading the way on reef education and ecology. Very impressive!!'

3.5. Public Awareness Results

The expedition aimed to build an understanding of coral reefs, as well as the diversity of local and global threats to coral reef habitats and resident species, to empower individual and community stewardship. The public awareness of the CS expedition was difficult to quantify, and so we instead recorded metrics for direct and indirect public awareness. The direct impact on 340 people included the 90 passengers and staff, as well as the 250 citizen scientists, identifiers, collaborators, and partners. Indirect awareness was estimated as 701,000 from a combination of advertising (reach of 500,000 people), media (100,000 people), social media (100,000 people), family and friends (500 people), and conference presentations (500 people).

3.6. Carbon Footprint Results

The trip distance was 1154 nautical miles, with 26.97 litres of diesel consumed per nautical mile for a total of 31,146 litres. We estimated that the large vessel used the equivalent of 83.5 tonnes of CO_2. We estimated that the four small vessels used approximately 1560 litres of unleaded fuel, equivalent to 4.2 tonnes of CO_2. We assumed that the expedition generator produced the equivalent of 3.0 tonnes of CO_2. We assumed that the 10 international passenger flights produced the equivalent of 125.0 tonnes of CO_2 and the 50 domestic passenger and crew flights produced the equivalent of 50.0 tonnes of CO_2. The total of these seven inputs was 268.7 tonnes or 4.48 tonnes of CO_2 per person.

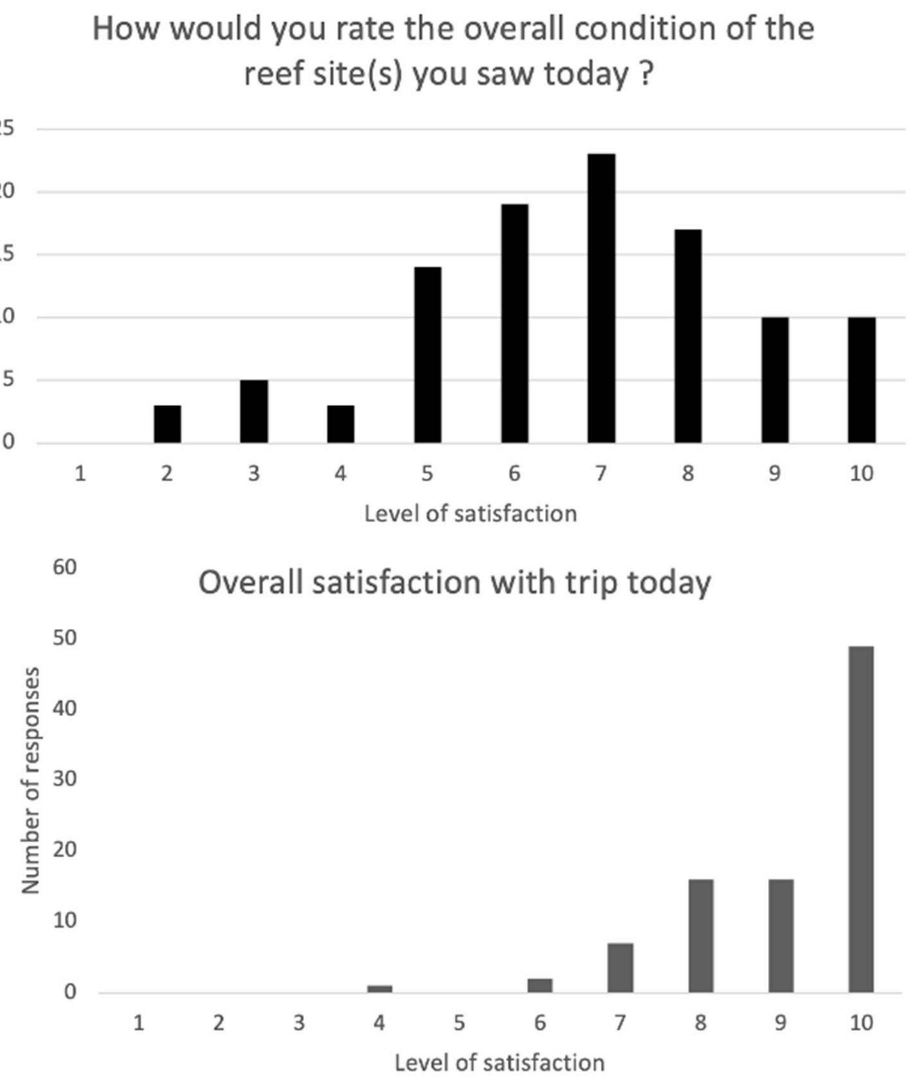

Figure 9. Participants rating of the overall condition of the reef site they visited (**top**) and their overall satisfaction (**bottom**).

4. Discussion

Citizen science (CS) projects involve members of the general public as active participants in research. While some advocates predict that CS can increase scientific knowledge production ('productivity view'), others emphasise that it may bridge a perceived gap between science and the broader society ('democratization view') [41]. We discuss how the first view was achieved in this project and how the second view had challenges, including behavioural, financial, and policy barriers.

4.1. Successful in Achieving Scientific Aims of the Expedition

The 2023 CS expedition to the GBRMP and CSMP directly engaged dozens of citizen scientists, many with no previous experience of the Great Barrier Reef or Coral Sea, in a far-ranging data collection and CS awareness-building effort. Despite challenges from cyclones, weather, people, and equipment, we generated data to support each of our five aims.

Citizen scientists increased their knowledge and understanding of coral reef environments and the challenges that they face in a warming world. By the end of the trip, citizen scientists had developed theoretical and practical knowledge of ten different marine CS tools, as well as learned the common and scientific names of hundreds of species of birds, fish, molluscs, and algae. With this suite of tools, citizen scientists contributed over 10,000 new data points (including thousands of valuable digital images and eDNA detection and sequencing data) to Australia's reef monitoring effort. Seagrass and algae samples were collected for donation to national and state herbariums with assistance from citizen scientists. In addition, the expedition team and citizen scientists have continued to communicate the findings through CS conference attendance, the production of an iNaturalist field guide [42] and participating as co-authors of this manuscript. The expedition team communicated the results of the expedition widely, including through the production of over 100 artworks, 2 media releases, conferences, presentations, and an estimated 100 social media articles, reaching an estimated 700,000 people.

4.2. Unsuccessful in Achieving the Carbon Footprint Aims of the Expedition

We were not able to leverage the carbon footprint and offset activity with concurrent fundraising to support a carbon-neutral expedition. This was surprising, as recent research by Andre et al. [43] indicates that 56.1% of Australians (and 69.0% of the global population) were willing to donate 1% (AUD 900) of their income to tackle climate change. Our estimate of 268.7 tonnes of CO_2 for 60 passengers and staff is equivalent to 4.48 tonnes of CO_2 (estimated at AUD 112) per person. This indicates a major difference in what people say they can do and what they will do. A comparison of the expedition footprint of 4.47 tonnes of CO_2 to that of the average Australian generating a carbon footprint of about 15 tonnes of CO_2 per year indicates high impact [44]. To reduce emissions, it is necessary to assign responsibilities, as mitigation represents a cost [26]. We discussed voluntary offsets with tourists during the expedition and there was a general mistrust of the process. Even though climate change is the biggest threat to the future of coral reefs worldwide [45], there is currently no relevant climate change or carbon offset policy for companies such as Coral Expeditions, Australian Geographic, and Reef Ecologic, nor for citizen scientists or visitors to the GBRMP or CSMP. Achieving climate neutrality in any endeavour is a three-step process that involves measuring the climate footprint, reducing emissions as much as possible, and offsetting the balance through direct action or funding. A citizen scientist, business, tourism industry, or government-led Environmental Management Charge or Reef Trust Offsets programme focused on climate impact and offsets may provide a solution.

4.3. Reef Health

The expedition team found that overall, the health of the GBRMP and CSMP during the expedition (late October to early November 2023) was good, which we quantified based on extensive observations of healthy corals, a diversity of species, and few observations of threats such as crown-of-thorns starfish, coral bleaching, or marine debris. The difference in coral morphology between the two marine parks is also an indication of continual recovery from regular cyclonic activity and back-to-back bleaching events in the CSMP [24], providing valuable data on differences between the two marine parks for managers. Given the bleaching being observed across large parts of the GBRMP and CSMP in the austral summer of 2023–2024, this information is particularly valuable. Until now, there have been few scientific comparisons between the two marine parks, and our research is one of the first to compare communities of fish, molluscs, and other biota. We also identified new records of fish, corals, and molluscs, along with significant observations of the spawning behaviour of fish in the GBRMP and mating turtles in the CSMP. An important heritage discovery by citizen scientists was a previously unknown anchor from the historic shipwreck *Foam*. This was a surprising result, as the wreck was rediscovered on 10 October 1982 and inspected by archaeologists nine times between 1982 and 2018 [46], with considerable effort, time, and technology committed to these inspections. We hypothesise that cyclones between 2015 and 2023 reduced coral cover and sand to partially uncover the previously hidden anchor.

4.4. Citizen Science Methods and Practices

Sampaio and Rault [11] suggest that citizen-led initiatives should be encouraged by governmental and non-governmental agencies, along with other stakeholders to strengthen the connection between the public and the scientific community. We agree, but with qualifications, as CS data have inherent advantages and limitations. CS's advantages include the ability to fill data gaps in regions of scarcity and expand monitoring beyond the constraints of research or authority budgets [47]. Another advantage is the ability to communicate science and inspire the public by using a diversity of communication tools. The CS limitations include a lack of reliability and rigour in the data generated, though this can be mitigated by providing educational material in lectures and field workshops alongside supervision by trained scientists prior to and during data collection. As an example with the iNaturalist CS method, recent research indicates that the accuracy of Research Grade taxonomic identifications is 95%, but this varies between taxa [48]. A further insight from Leona Kustra (one of the citizen scientists on the expedition and co-author of this paper) was that '*when multiple citizen science platforms are introduced and used by scientists, it can be inspiring for citizens to explore each and determine which ones best suit and motivate them. Offering multiple marine citizen science tools and having the citizens try each tool alongside scientists works to increase confidence amongst citizens which then are more likely to adopt at least one citizen science tool. Since marine citizen science is underrepresented, increased offerings and having scientists introduce, use and support citizens in their learning and use of citizen science platforms may increase acceptance, contributions and advocacy*'.

Our experience is that multiple CS methods and tools increased participation, data collection, and enjoyment, ultimately resulting in a better understanding of the marine environment. When used together, methods and tools that measure reef health, such as Eye on the Reef, Great Barrier Reef Census, and CoralWatch, provided replication and increased confidence in the data. Use of multiple tools from one vessel and a coordinated project compared to individual tools from multiple vessels and disconnected projects, arguably reduces carbon footprint and increases sustainability.

CS involving community participants can improve knowledge of marine parks by providing supplementary information for management. The addition of CS is complementary to traditional research and monitoring programmes and can therefore increase the availability of data on free-to-access data repositories. This is especially notable when the data collected are from remote locations, where traditional research and monitoring can be sparse due to logistical and budget constraints. It also provides participants with an opportunity for a hands-on, enriching experience and understanding of marine park values.

Of the ten CS tools available during the 2023 Citizen Science of the Great Barrier Reef expedition, the most popular was iNaturalist. Citizen scientists found it easy to use, and the extensive support of online taxonomic experts supporting identifications meant that the data quality was high. Over one-hundred times more fish observations were made with iNaturalist than with Eye on the Reef. Roberts et al. [12] reported that iNaturalist recorded 1.2 to 5.5 times more fish species than structured surveys resulting in significantly greater annual species richness estimates. The expedition observed and recorded 452 fish species, about a third of the total estimated 1500–1625 fish species known to the region [49], though the ability to make inferences about species abundance with iNaturalist data remains limited [50]. The disadvantage to this tool is that it requires access to an underwater camera for photography, which may be limiting in some cases.

The application of iNaturalist and eDNA metabarcoding in tandem facilitated the detection of a large range of biologically and economically important taxa, as well as those that may be under threat. However, there were also gaps in our taxonomic assignments using these tools. A major shortcoming of the eDNA approach is the poor coverage of molluscan and holothurian species using existing metabarcoding assays. Indeed, although based on eDNA sampling in a subtropical estuary in Queensland, Australia, Downie et al. [33] found low detection rates for oysters and mussels using nearly the same set of metabarcoding assays that we applied here, which the authors attributed to primer bias, poor resolution of the available assays, and incomplete genetic reference databases. Similarly, although we did detect Cardiidae in 2 out of 16 replicates at Orpheus Island in the GBRMP, a taxonomic family that includes giant clams, our low rate of detection with eDNA does not reflect their diversity at several locations that we visited on the expedition, which in this case may also relate to low rates of DNA shedding from these invertebrates. If we were interested specifically in this family at the expense of all the rest of the flora and fauna in our sample, we could redesign and reapply more targeted genetic assays. This refinement is facilitated by the fact that all the eDNA samples were archived (frozen at −80 °C) in perpetuity and therefore available for re-examination in the years to come.

5. Conclusions

We conclude that coral reefs are under global anthropological and natural threats and citizen science provides an opportunity for scientists and the community to collaborate, learn, share knowledge and take action together. The scientists who led the expedition inspired citizen scientists to learn and use ten different marine CS tools and they contributed over 10,000 new data points (including thousands of valuable digital images and eDNA detection and sequencing data) to Australia's reef monitoring effort. There were challenging discussions about climate change and carbon footprint between scientists and tourist citizen scientists and we estimated the total and individual footprint per person, but we were not able to achieve consensus on actions to reduce, mitigate, or offset.

We propose four recommendations to leverage the lessons learned from the 2023 Citizen Science of the Great Barrier Reef and Coral Sea expedition to assist future marine CS and sustainability activities.

1. *Review strategy*: Review the Queensland citizen science strategy (Queensland Government 2021) with a specific focus on marine CS in Queensland and adjacent Australian waters applied in an ecotourism context. Allocate resources to encourage integration and prevent duplication of effort among scientists, citizen scientists, tourism operators, government and indigenous rangers. Encourage citizen science participation in education, field work, data entry and analysis, and the communication of results.

2. *Measure changes over time*. Repeat the expedition in 2025 (2 years) and 5 years (2028) to compare CS methods, the biodiversity detected, and reef health.

3. *Drive sustainability*. Individual researchers lead by example and ensure a carbon neutral footprint. For tourists and businesses, we recommend an Environmental Management Charge or Reef Trust Offset or fee based on our estimated carbon impact for passengers and staff to ensure future expeditions are carbon-neutral.

4. *Encourage participation*. Work with all sectors of the reef community to encourage people to take part in collaborative CS to help better understand the reef, the challenges that all reefs face, and the sustainable solutions that can be brought to bear to preserve them for the future.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su162411019/s1. Supplementary S1. eDNA protocol (References [51–58] are cited in the supplementary S1); Supplementary S2. Citizen science expedition—Great Barrier Reef Visitor survey—October 2023; Supplementary S3. eDNA phylogenetic trees based on seawater samples collected at reefs in the Great Barrier Reef Marine Park (GBRMP) and Coral Sea Marine Park (CSMP).

Author Contributions: The expedition was led by A.K.S. and he invited and selected guest lecturers for the expedition and co-authors for the paper. J.D.D. led the eDNA studies. S.J.T. led the marine vegetation studies. T.M. led the heritage studies. All co-authors contributed to the conceptualisation, data curation, investigation, formal analysis, methodology, project administration, and visualisation, as well as contributed to writing the original draft manuscript as well as writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: Environmental DNA sample processing was supported by Academic Career Support funds to J.D.D. at Griffith University.

Institutional Review Board Statement: Research involving human subjects, human material, or human data were performed in accordance with the Declaration of Helsinki. Social surveys were co-designed and conducted under Privacy Act 1988 (Cth) and the NH&MRC National Statement on Ethical Conduct in Human Research (2007, updated 2018), and ethics were approved by CEO Reef Ecologic.

Informed Consent Statement: Scientific Research in the Coral Sea Marine Park was permitted under Permit Number PA2023-00117-1. Education in the Great Barrier Reef Marine Park was permitted under Permit Number G17/39528.1. Entry to a protected zone under Section 23 of the Underwater Cultural heritage Act 2018 was permitted under Permit No 100847.

Data Availability Statement: All raw data needed to replicate this study and statistical analyses are available as Supplementary Materials. Raw environmental DNA sequence data are also available as .fastq files on the NCBI GenBank Sequence Read Archive (BioProject Accession Number: PRJNA1109436).

Acknowledgments: We acknowledge the Traditional Owners of country throughout the Great Barrier Reef region, and all of Australia, and recognise their continuing connection to land, waters, and community. We pay our respects to them and their cultures, and to elders past, present, and emerging. We thank Australian Geographic, Coral Expeditions and Reef Ecologic for coordinating the 2023 Citizen Science of the Great Barrier Reef and Coral Sea expedition. We particularly thank Tamara Sweeting and Nicky Henderson for planning and Captain Simon Buckeridge, Ben Ruzicka, and Katie Tuesley for operations. We acknowledge the enthusiasm and data provided by the guests and staff and their ongoing commitment to communication. The authors would also like to thank Shaun Wilkinson, Amy Gault, Tiso Ross, and Susan Welsh from Wilderlab NZ Ltd. for logistical assistance with environmental DNA sample processing. The authors thank Al Songcuan for assistance with preparation of Figure 1 and statistical advice. Reef Ecologic is a Bcorp and carbon-neutral company and measured and offset the estimated carbon emissions of two authors (AS, JS) participating in this expedition and research.

Conflicts of Interest: Authors Adam K. Smith, Joanne Stacey were employed by the company Reef Ecologic. Author Toni Massey was employed by the company Cultural Heritage Management Australia. Author Paul E. Hardisty was employed by the company P38 Media and Consulting. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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