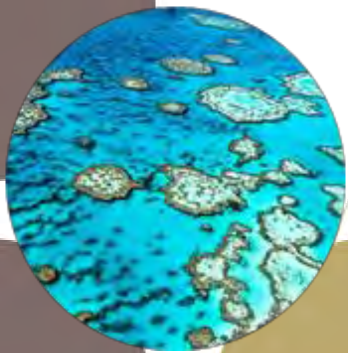
Monitoring Through Many Eyes: Spatially enabling people to protect the Great Barrier Reef



Stage 2 – Report 1/4

Summary document

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About us

The Monitoring Through Many Eyes project is a multidisciplinary research effort designed to enhance the monitoring of the Great Barrier Reef. The project aims to create a virtual reef by geotagging underwater photos and videos contributed through citizen science. These will be used to create immersive environments that will help to improve estimates and predictions of the health of the Reef. Our mission is to deliver new know-how in visualisation and spatial statistical modelling, new spatial products, and a new avenue for the public to engage in monitoring the reef.

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Executive Summary

The aim of the Monitoring Through Many Eyes project was to design and develop an innovative software platform to engage citizens in globally important science. This interactive spatial platform is the first of its kind, providing to the community an opportunity to contribute to, and share in, unique visual and immersive experiences of one of the most important ecological environments on planet Earth, the Great Barrier Reef (GBR). This work is timely and important, due to the international and national imperatives to better manage the Reef, as well as the increasing stresses on the Reef such as coral bleaching, land-based pollution, and Crown-of-Thorns starfish (COTS).

The novel platform described here allows recreational and commercial divers to geotag their photos and videos to a spatially referenced, online digital Reef. These are used to create visual and virtual reality environments that can be viewed by the public and also by reef experts. Data about aspects of reef health can be classified by citizens or elicited from the experts. These data are then used to improve statistical models, which can be refit automatically as new data is submitted. The outputs of these models provide the most up-to-date information available for monitoring and management of the GBR.

The platform thus provides an online, reef decision-support system for government that also engages the general public in assisting scientists to preserve this natural wonder. A key component of this is the ability to visualise the results of reef-health modelling on an online interactive map. In addition, managers and researchers can download model outputs for use in their own studies and assessments.

Our prototype system utilises state-of-the-art statistical modelling techniques, integrated with high-quality web interfaces for data collection, reef image uploading, and further viewing. In particular, this project extends the state-of-the-art by providing novel virtual-reality experiences for the general public to improve monitoring via 5 specific objectives:

1. *Developed a system that allows the community to engage in monitoring the GBR*. Created an interactive, spatially referenced map of the GBR to which crowd-sourced geo-referenced imagery and other relevant information can be attached.
2. *Developed applications to explore 2D and 360-degree visual images of underwater reef environments*. Developed and applied the tools to convert the contributed imagery to 2D or 360-degree visual and immersive underwater environments at key locations.
3. *Elicited expert information using these contributed images.* Created visual and virtual reality environments based on the images; developed and applied methods for exposing a range of experts to these new environments, and developed ways to extract specific quantitative and qualitative information about indicators of reef health (e.g. coral cover and reef aesthetic value).
4. *Created statistical predictive models.* Developed and trialled statistical methods for using the elicited responses and other extant geo-referenced information to enhance spatial models that can be applied to the whole-of-the reef, which could be used to create 'reef health maps' in the future.
5. *Evaluated the utility of the models*. Assessed the potential use of these models for facilitating management decisions, designing adaptive monitoring programs, and expanding public awareness and engagement.

This present report provides a general overview of these 5 objectives, with summaries of each component of the framework and future directions.

Although the prototype platform was developed for a citizen-science project in the GBR, the concept is transferable to other systems and data types. A similar workflow could be implemented in catchments to monitor and model river discharge in near-real time. The existing platform could be modified to solve other catchment-monitoring issues where large amounts of data are needed to enhance management strategies. Information can be automatically extracted from high-resolution remote-sensing data to help monitor illegal land-clearing activities or changes to ground cover on public and private lands.

There are also opportunities to significantly extend the visualisation and VR capabilities of such a system. Scenarios represented using model predictions or real-life imagery could be viewed in 2D, or in immersive 360-degree or 3D environments to help users understand the spatio-temporal drivers of events such as floods in urban areas, droughts in agricultural landscapes, or flooding effects on the Great Barrier Reef. Broader community stakeholders may also benefit from narrative style 3D visualisation playing out scenarios in a direct story-based manner that will help communicate complex environmental processes, model results, and uncertainty. The use of immersive and interactive visualisation provides a rich set of tools to encourage the formation and integration of stakeholders in the Reef's future.

Introduction

System Overview

The overall structure of the system is broken down into four major components: Web Interface, visual and virtual reality (VR) Experience, Modelling, and the Workflow Framework (Figure 1).

Figure 1. Overview of the Monitoring Through Many Eyes project components.

Web Interface component

Our prototype provides an integrated, single access-point web-interface showing a map of the reef, uploading facilities for imagery from citizen scientists, enabling the VR elicitation interface to load imagery via QR code access, and providing access to the modelling results. Behind the scenes a complex workflow system processes the imagery, coral cover data, and elicited information, which is used to produce an updated coral cover map on the interface. An image of the web interface is shown below (Figure 2).

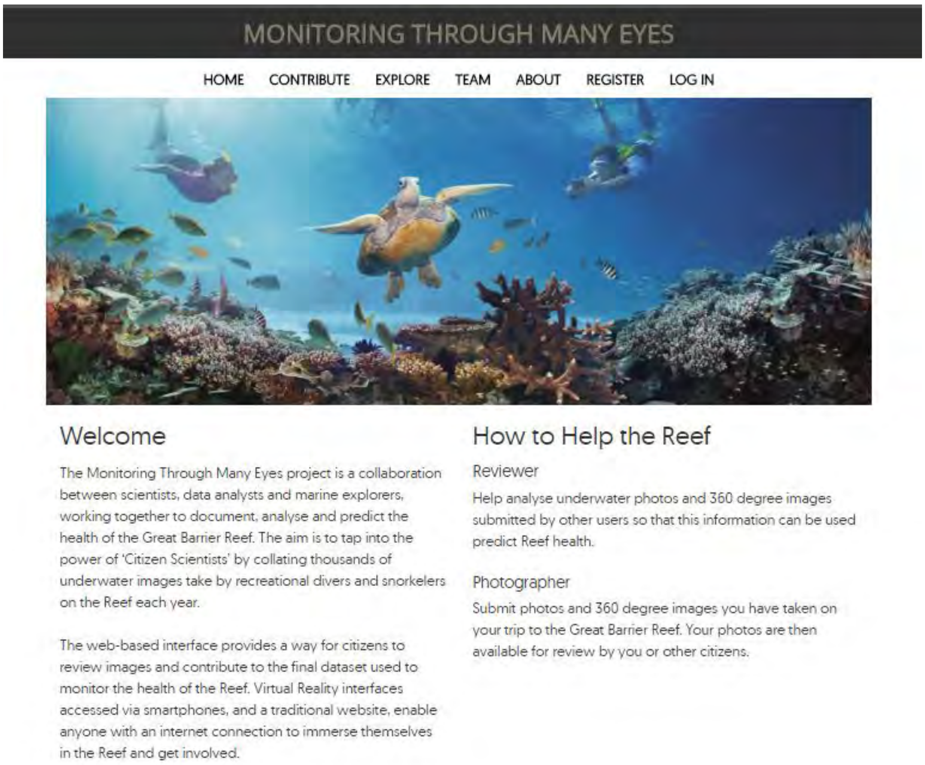


Figure 2. Initial web interface screen for the Monitoring Through Many Eyes project.

Visual and Virtual Reality Elicitation component

The prototype citizen-science platform provides a 360-degree elicitation environment, along with a web-based 2D environment to enable access from all user platforms. This elicitation environment has been used to garner expert knowledge from scientists, enhancing the spatial predictive models we developed. Our previous research as a group has indicated the effectiveness of utilising VR headsets to elicit knowledge from stakeholders in business applications (Harman 2016). In short, visually overwhelming information at a location stimulates memories in the mind of the expert, which can be used to produce better model predictions. We show that this approach also works well in the reef context. An example image from our VR elicitation system is shown in Figure 3.

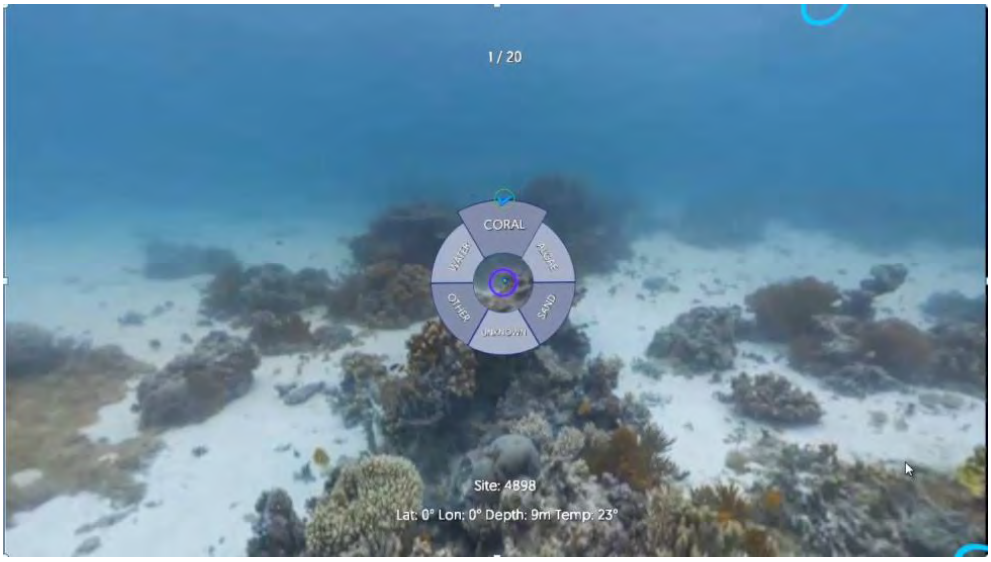


Figure 3. A 360-degree image of the reef. The circles represent elicitation sample points in the image and the menu is used to classify each point.

Modelling component

The models have been designed and developed to incorporate a range of inputs, including data observed in the field, information extracted from the contributed citizen-science images, expert information elicited from visual and immersive environments developed from the images, and other ancillary sources. Two studies have been performed to highlight the functionality of the system as-a-whole. The primary study, the coral cover model, was developed to fit to data from professional monitoring programs, as well as citizen-contributed data, and used to produce spatially explicit predictions with estimates of uncertainty for coral cover across the GBR. This model explicitly accounts for various sources of uncertainty in the different data sources, including coral classification method, image quality, annotator quality, and image extent. The predictions from the coral cover model can be viewed on the “Explore” map online. A complementary study was performed to explore and understand the drivers of reef aesthetic values, which were elicited from citizens, scuba divers, and marine scientists within an innovative VR environment. This second study was outside the scope of the original project but was contributed as additional research to demonstrate the power of the VR technology.

Workflow Management component

In order to support each component within the prototype system, we developed a scalable cloud-based, backend workflow module. This module integrates information obtained from the images uploaded on the web-interface into a database for processing by the statistical modelling module. It regularly runs modelling scripts, automatically generating new predictive maps that are displayed on the web interface. In addition, this workflow module provides the background infrastructure for the web interface, allowing image data to be displayed on the screen. This module runs in the background and provides the capability to scale up the storage and processing of this system to provide for a large community of citizens and experts using the system worldwide.

1. Web design


THE VIRTUAL REEF
HOME UPLOAD EXPLORE CONTACT REGISTER LOG IN
Virtual Reef

1.1 Web Interface Overview

This section describes in detail the web interface, its various components and background software services used to support the interface within our prototype. Related services encapsulated in data and processing modules are described in later sections.

The website component of the application has several key roles in the delivery of the project functionality. It allows a user to:

- Learn about the project, its core objectives and the role citizen scientists or subject matter experts can play in the contribution of imagery and elicitation of analytical data.
- Upload and contribute both 2D and 360-degree imagery to the project for users to annotate and locate within the project bounds of the GBR.
- Explore the imagery and modelling outputs in a web based maps engine.
- Register a user account and login, to allow a personalised contribution experience

The website component also provides background services in the form of Javascript Object Notation (JSON) Representational State Transfer (REST) services to allow the VR application and to interact with the website database via QR codes. Relevant imagery is loaded and elicitation data are submitted back into the database for consumption by the modelling architecture. Additionally, these REST services are utilised by the predictive modelling framework to both retrieve and store data.

A main menu is provided on the front page to traverse to the various functionalities of the prototype (Figure 4).

Figure 4. Enlargement of banner and menu displayed on the main website page.

Broadly, the menu structure reflects the main functionality of the website:

1. Content Pages - non-interactive information pages (See Section 1.2) accessed via *Home*, *Team* and *About* menu options;
2. Image Contributions - image upload facilities for experts and laity (See Section 1.3) accessed via *Contribute* menu option;
3. Data Exploration - map-based image and spatial model interface (See Section 1.4) accessed by the *Explore* menu option;
4. Membership Services - provides upload and elicitation activity information for Registered users (See Section 1.5) accessed via *My Profile* menu option. Note that, the webpage access is currently restricted and so the *Register* page is not currently active.

We now explain these in turn.

1.2 Content Pages

There are several non-interactive content pages within the website, providing information on the following subjects:

- **Home Page** – Project overview and introduction, project objectives and graphical banner as the entry point to the website.
- **Team Page** – A detailed list of the project team members and their various roles within the project.
- **About Page** – a more detailed exploration into the project technologies, workflow and technical framework.

1.3 Image Contributions

An important aspect of the project is the contribution of both 2D and 360-degree imagery for the website. This imagery can come from both citizen casual divers, and expert professional divers. To begin adding their photos, a user selects the "Contribute" menu item.

A user must be authenticated (via creating a user account) to use the contribution form, ensuring a higher quality of data and the allocation of weightings to a user's ability to provide images of a certain quality. The database has been structured to capture information related to this capability, but has not been implemented at this stage of the project. Contributions made by a user can be seen in a simple list format on their "My Profile" page once completed.

Using a traditional upload selection or drag and drop methodology for a JPG file, the following information gathering process is completed before submitting the imagery (see Figure 5).

The file is selected from the user's local computer or device and uploaded to the page in the 'client' environment, allowing any available geo-located EXIF metadata to be extracted. If no geo-location metadata exist, the user is requested to identify the location of the photo on a map.

Once located, data relating to the dive spot is captured from the user, including:

- Is the photo a 360-degree image, or a traditional 2D photo?
- Did the user identify any Crown of Thorns starfish (CoTS) within the photo?
- Did the user identify any signs of Coral Bleaching within the photo?
- At what depth was the photo taken, in metres?
- If available, what temperature in Celsius was the water at this location?

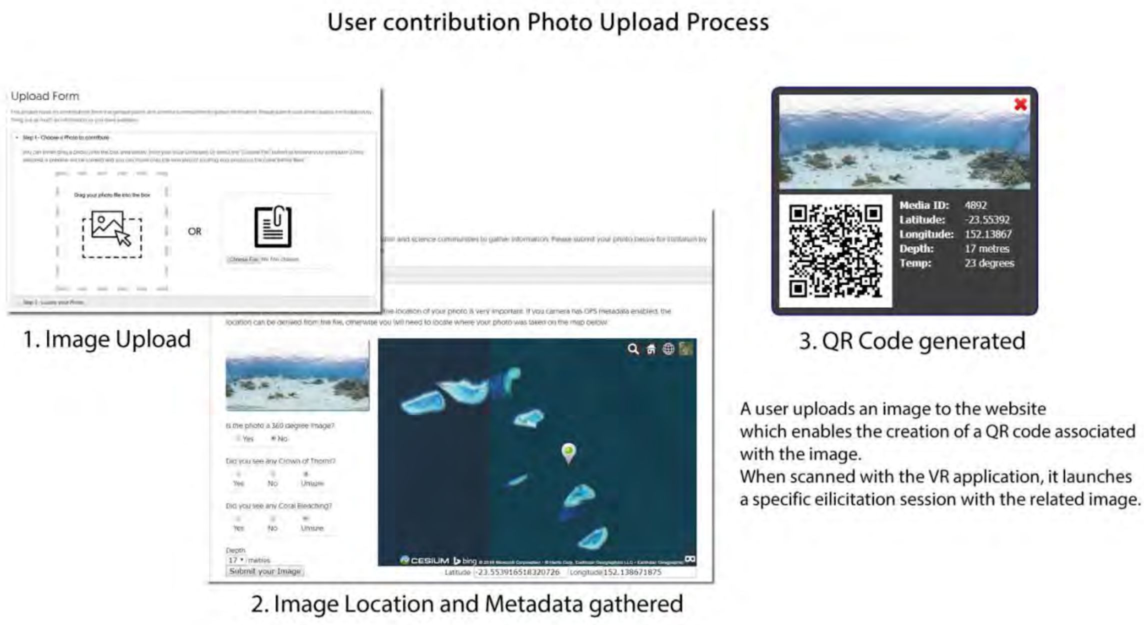


Figure 5. Contribution phases including 1. image upload, 2. location and metadata and 3. final QR code generation.

Upon completion of the upload form, the file and metadata are submitted for processing into the framework, including the renaming of the file to a unique name, resizing the image for display on the website and in the VR environment, and the generation of thumbnails for use in the map and popup interfaces. At this point, a unique Media ID is generated for each image submitted, which identifies the imagery and location throughout the interface, data processing and modelling. This is shown as a QR code on the dialog to be used with the VR application we describe in the Software Development chapter.

1.4 Data Exploration

The Explore page exposes the core of the application. It can be used to view the predictive modelling output across the entire reef, or to navigate and elicit images in the web based environment. Additionally, it provides a gateway into the VR environment for both 2D and 360-degree elicitation through the display of a QR code, which loads an elicitation session for the given image when it is viewed using the VR application.

To access the different datasets, the user selects from either the photography or modelling layers in the floating menu over the 3D map (Figure 6).

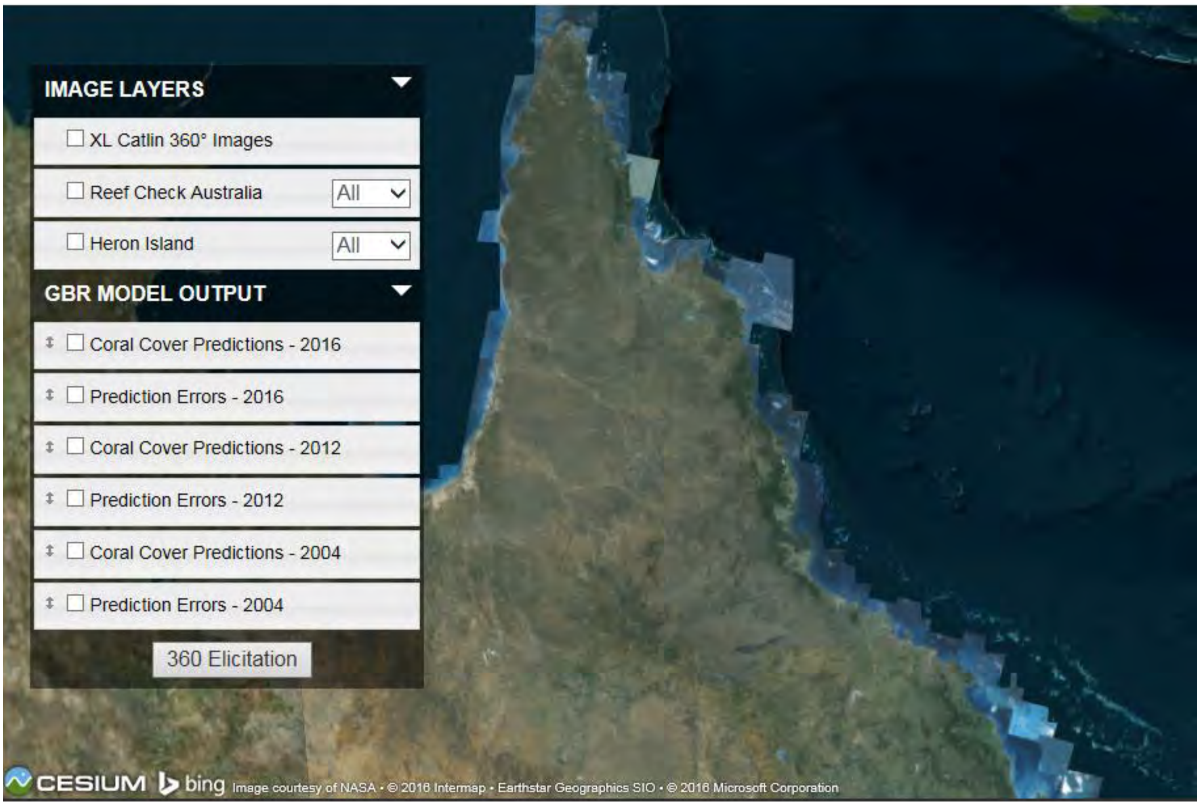


Figure 6. Multiple layers are available within the Cesium map, which provides an overview of the Great Barrier Reef, Queensland.

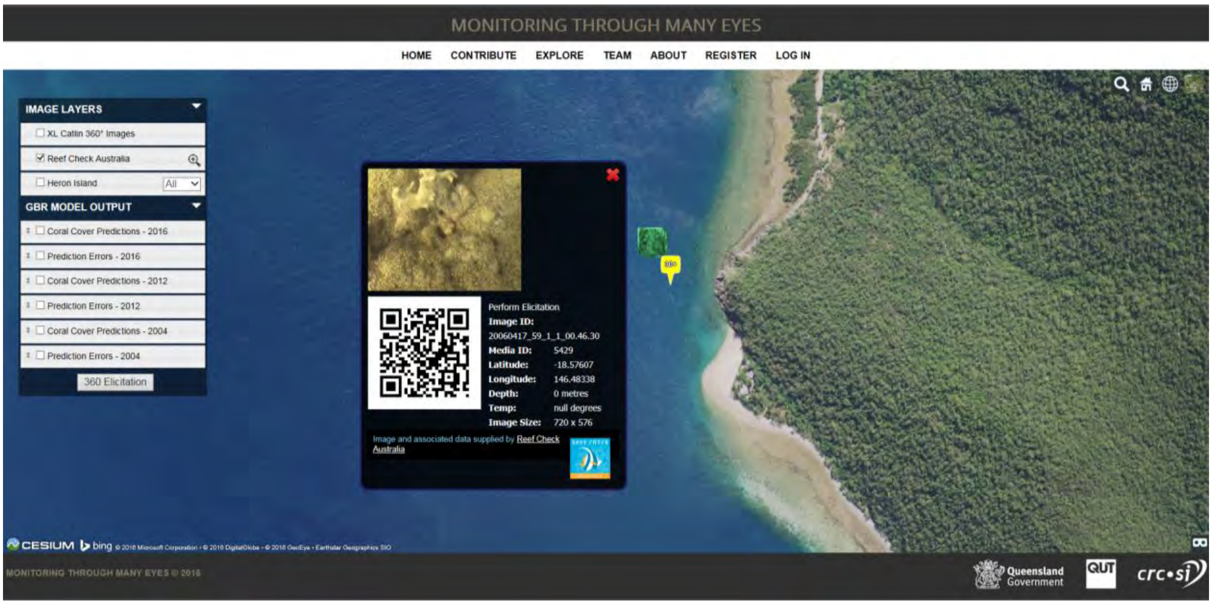


Figure 7. Image layer with Reef Check dataset active and one image highlighted with its QR code.

Imagery layers have the capability to be turned on or off, zoomed into the viewport, and for larger datasets a dropdown box allows the selection of a subset of the data for that layer (Figure 7).

Modelling layers also have the capability to be turned on or off and can be re-ordered through a simple drag and drop interface, allowing layers of interest to be brought to the top of the layer stack, becoming visible. Additionally, any of the modelling layers can be faded in or out, through an alpha sliding fader on a per layer basis (Figure 8).

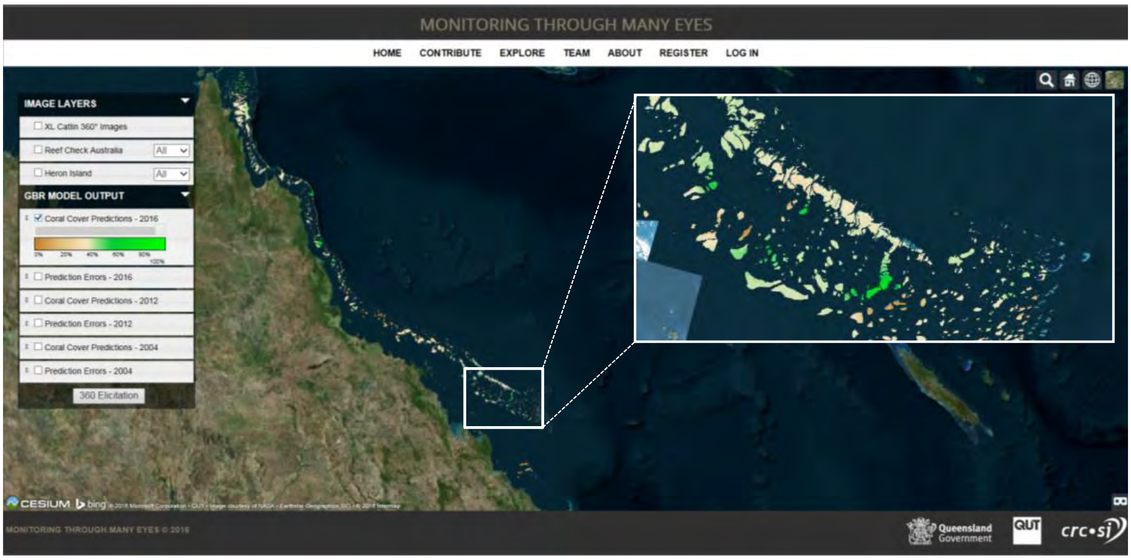


Figure 8. Example model prediction layer for 2016, with a map inset showing a more detailed view of the prediction layer.

When the user selects a photo, a partially transparent 'popup' window appears over the map, which can be dragged to relocate its position on the map (Figure 7, Figure 9). The window contains the following elements for each photo item selected:

- Preview image of the larger 360-degree image;
- A QR code that is viewed with the VR application, allowing the user to view the image in their headset;
- Image metadata pertaining to the location and depth; and
- An image source attribution where the image has been supplied by a third party.

1.5 Membership Services

To contribute photos to the service, a user is required to create an account and login. This is required to both reduce automated image uploading by malicious non-authenticated users, and to identify and eventually weight the quality of users' contributions.

Creating a sense of ownership, by allowing a user to see their uploaded photos and elicitation contributions, increases user engagement and subsequently the quantity and quality of the data collected. The My Profile page, available once the user logs in, displays this information (Figure10).

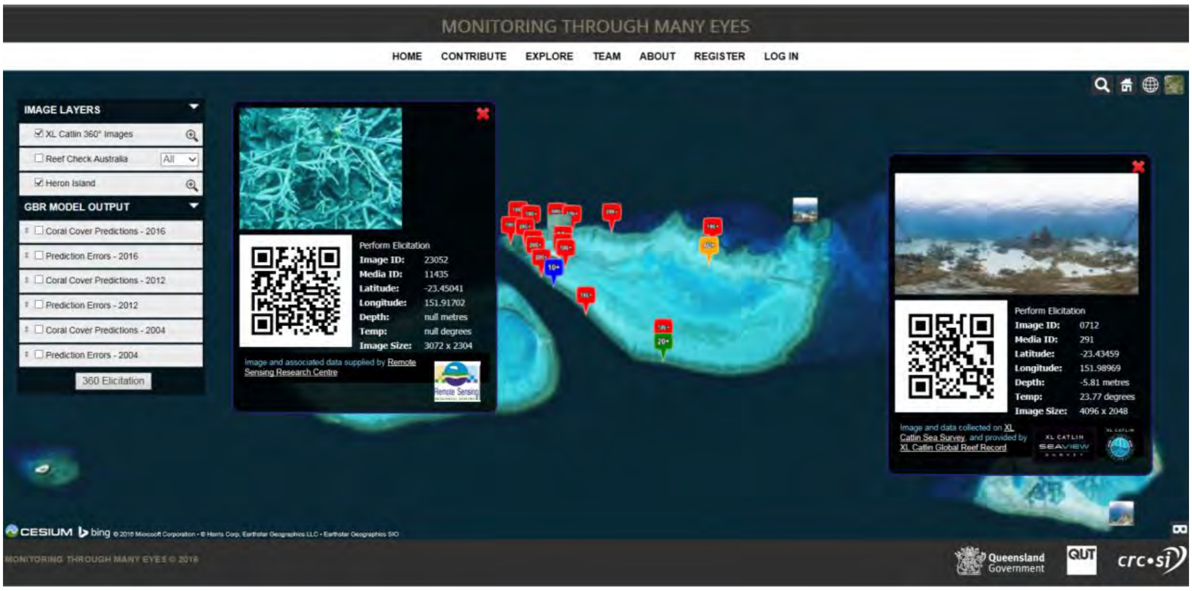


Figure 9. Image attribution information is attached to each image uploaded and displayed in the popup window.

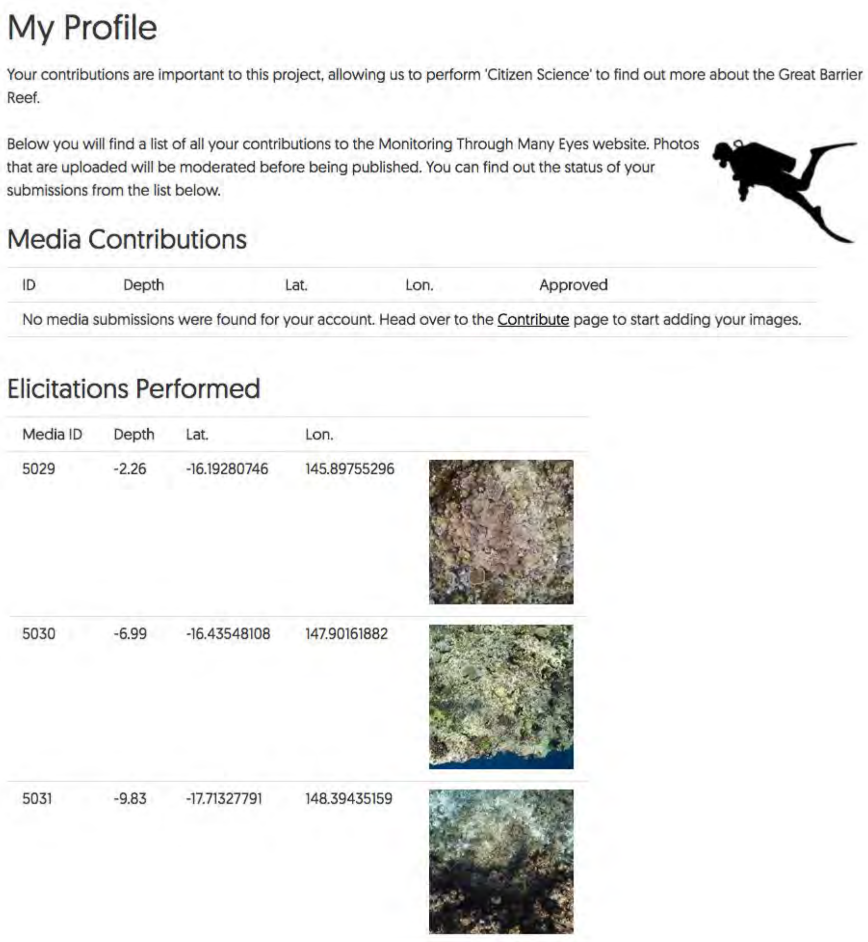


Figure 10. My Profile page from the website showing uploaded images and elicitations performed by a contributor.

To create an account, a user must only supply a username and password on the registration page (Figure 11). Once logged in, they can use the Contribute page to add photos for elicitation. They can also perform elicitations themselves, with their authentication token (UserID) integrated and passed through the QR code to the VR environment. This persists when performing web-based 2D elicitations so that they can return to the image to generate new elicitations.

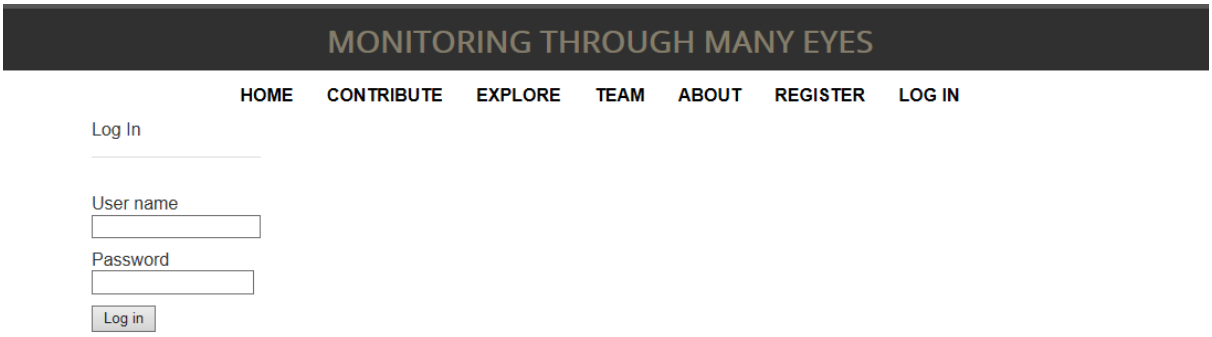


Figure 11. User registration page.

1.6 Prototype Website Access

The complete prototype application is currently hosted on the Queensland University of Technology (QUT) network, accessible via virtual private network (VPN) only. It can be viewed at http://eyesonthereef.qut.edu.au because this version contains proprietary datasets which were used fit and validate statistical models and data visualisation outputs. Additionally, it contains the upload and membership features.

In addition, a limited version of the website has been released in the public domain, primarily to showcase the use of the QR code to VR Application mechanic to load and view a licenced selection of both 2D and 360-degree imagery. In addition, users can explore the model outputs within the Cesium map. The external website can be viewed at https://www.virtualreef.org.au.

2. Virtual Reality & Elicitation






2.1 Software development

The virtual reality (VR) application is a mobile phone based application designed to run on Android phones running within a Samsung GearVR headset (Oculus, Figure 12). There are two modes of operation that can be accessed within the app; a coral cover annotation elicitation mode, and a reef aesthetics survey mode. These modes are detailed in Sections 2.1.3 and 2.1.4.

The VR application supports both standard 2D and 360-degree images for elicitation. 360-degree images are stored in an equirectangular projection which look distorted when viewed as a flat 2D image, but look correct when 'wrapped' onto the inside of a sphere, with the user placed in the centre of that sphere. The user is required to physically look around to view the entire 360-degree image. In contrast, standard 2D images are displayed as a 'virtual cinema screen' with the image presented in front of the user as though on a large screen. The image is slowly scrolled up/down/left/right following the user's head movement, enabling the user to access all parts of the image for elicitation.

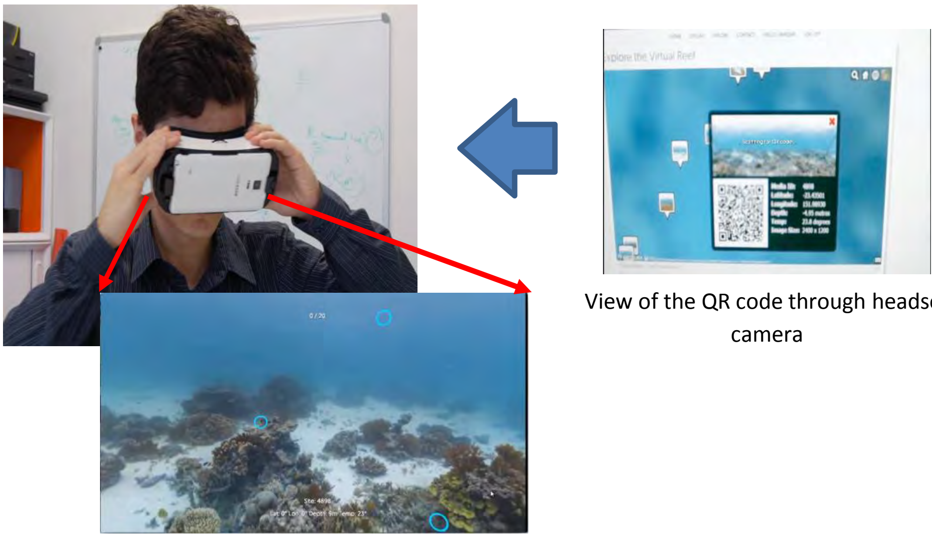
The mobile application has been developed using the Unity game engine environment with additional scripting written in the C# language. The current implementation has focused on the Android-GearVR combination of technologies, primarily to take advantage of the touch button on the side of the GearVR headset. Support for the GearVR headsets is also conveniently a built-in feature of the Unity platform. Future development could relatively easily expand upon this to also support iPhone and newer Google mobile devices, across the range of Google Cardboard and Daydream compatible VR headsets.

Figure 12. Image of GearVR headset which can be used with our VR elicitation and immersive reef experience components.

One restriction of GearVR mobile applications is the requirement to sign each mobile device running the application with a unique Oculus signature. This signature file is generated on the Oculus developer portal website and placed within the Unity project before the application is built and deployed to the mobile device. This restriction prevents us from easily distributing the application and deploying onto phones, without using the Unity build and deployment process. This can only be avoided by submitting the application to the Oculus VR online store, which was not an option for this stage of the project. More information about application signing can be found here https://developer3.oculus.com/documentation/publish/latest/concepts/publish-mobile-app-signing/. We are happy to provide a binary of the Android application on request.

2.1.1 Initiating an elicitation session

Both annotation and survey elicitation modes make use of a QR code mechanic, which is used to select an image on the reef and initiate a VR session at that location. To initiate an elicitation session for a selected image, the user scans the associated QR code for the image using the camera on the mobile device being used with the VR headset. A pass-through image as seen by the camera is displayed allowing the user to scan the code while looking through the headset (Figure 13).



View of the QR code through headset camera

Figure 13. Users look at the QR code through the headset camera to retrieve a 360-degree reef image. Image collected on XL Catlin Seaview Survey, and provided by XL Catlin Global Reef record.

Each QR code uniquely represents a reef image linked to a geo-located photo (both standard 2D or 360-degree photos). The QR encodes a string which maps to a unique image (i.e. a media ID) and associated metadata, and optionally, the User ID of a registered user. As an example, if the string "/api/media/5938" is encoded into the QR code, scanning this code would load the elicitation image with ID=5938 and instigate an 'anonymous' elicitation session for that image. When the session is complete, the user submits their results which are then recorded in a database (Figure 14).

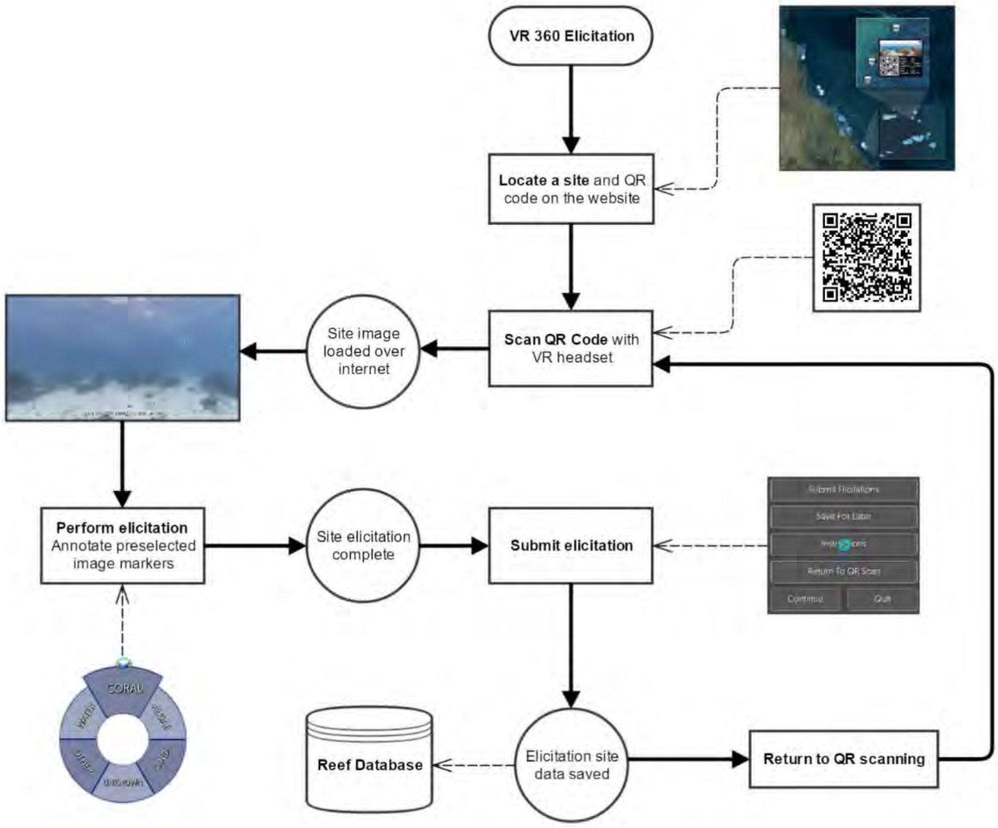


Figure 14. A flowchart of the full annotation elicitation process from QR code scan to submission of elicitation results into the database.

The above example is an anonymous elicitation session because no user identifier is associated with the elicitation, and therefore the submitted elicited information is also anonymous. This is useful when multiple people are performing elicitations using the same device, without the need to logout/login. The downside however is that the elicited information may not carry as much weight or significance, as there is no way of determining the expertise level of the user that submitted the results.
Alternatively, the QR code can also encode a specific user ID, which is appended to the code when a registered user is logged into their account on the website. For example: "/api/media/5938?UserID=c51e7bf4-7406-4b4e-950b-92b7ef2e470f". This User ID identifies the logged in user. When the elicitation results are submitted, the system is used to associate the responses to that user. This allows the results to be weighted based on the user's determined expert level.

2.1.2 Input data format

When a QR code is scanned using the VR application, the encoded media ID is used to query a REST to obtain the required information for the requested site. The service responds with a packet of information about the site in a text-based JSON format (Figure 15). An example response from the REST service is shown below:

```
{
        "elicitations": [],
        "mediaID": 5938,
        "sourceURL": "20070923_93_2_2_00.10.36.jpg",
        "thumbSURL": "54x54/fdd05e78411545e2887e20b11eabe174.jpg",
        "thumbLURL": "400x150/fdd05e78411545e2887e20b11eabe174.jpg",
        "fileName": "fdd05e78411545e2887e20b11eabe174.jpg",
        "mediaTypeID": 1,
        "imgSizeX": 2048,
        "imgSizeY": 1024,
        "tempCelsius": 26.7,
        "isApproved": false,
        "approvedByUserID": b52e7bf4-4a06-4cfe-911b-92b7ef2e335d,
        "approvedDate": "2016-09-13",
        "imageID": "20070923_93_2_2_00.10.36",
        "isUserSubmitted": false,
        "lat": -18.57994115,
        "lon": 146.4814863,
        "depth": 8.11,
        "crownOfThornsSighted": null,
        "coralBleachingSighted": null,
        "userId": "c51e7bf4-7406-4b4e-950b-92b7ef2e470f",
        "mediaSource": "ReefCheck"
    }
```


Figure 15. JSON listing of image data for image 5938.

Some of the fields are used for different software modules in the system, such as the online web map interface. The most important fields that are used to initiate the VR session are listed below:

- Media ID, uniquely representing an elicitation site image,
- A media ID that is used to determine whether a 360-degree photo or a standard 2D photo
- A URL that points to the full-size captured image for display in the VR environment,
- The geospatial location of the site where image was taken, as latitude / longitude, and depth if available,
- The temperature in Celsius of the water when the photo was captured, if this information exists,
- The resolution of the image,
- The “elicitations” field is used to hold the user responses submitted from a completed elicitation session.

2.1.3 Coral cover annotation

The coral cover annotation mode has been developed to estimate the percentage of coral cover visible within each image. This is achieved by asking the user to classify a random scattering of elicitation points as one of six different categories (coral, algae, sand, other, water, or unknown; Figure 16). The primary category of interest for this application is coral; however, similar models of benthic cover could also be based on the elicitation.

The six categories are mutually exclusive and only one option can be selected. The example output data below represents each of these as a single value between 0 and 5 (e.g. 0=Unknown, 1=Coral, 2=Algae, 3=Sand, 4=Other, 5=Water).

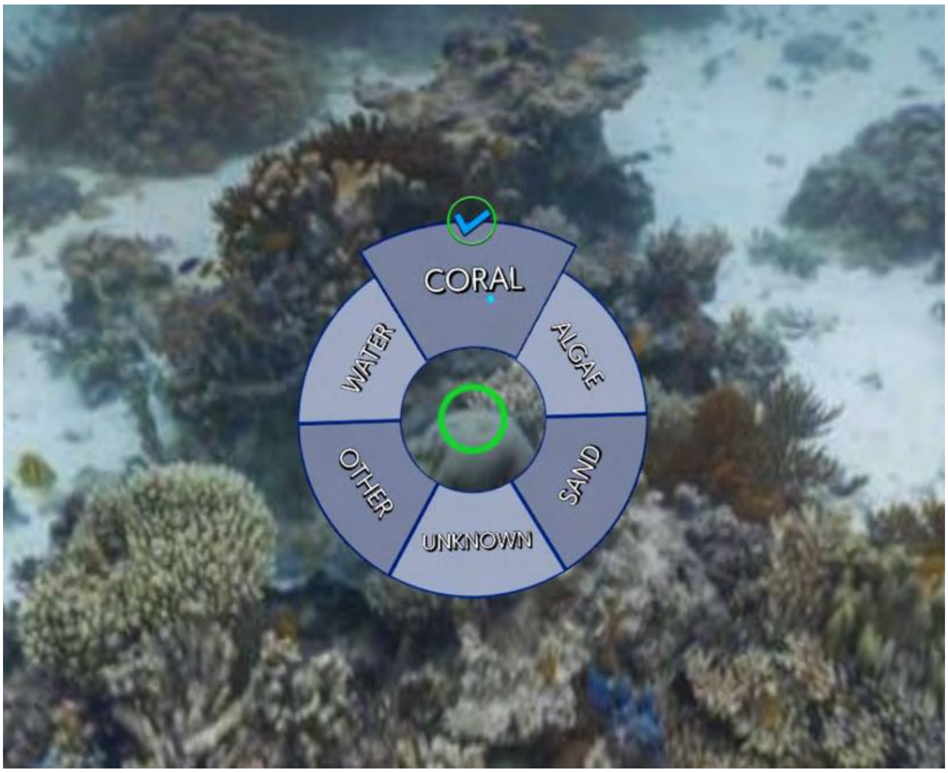


Figure 16. Coral cover elicitation interface menu.

Annotation points are stored as normalised UV coordinates (i.e. X, Y image coordinates scaled to the range 0 to 1 for mapping to a 3D model surface) and a single integer value that represents the user selection for that annotation. A date/time stamp is also included to record when each point was annotated. An example of the user submitted data from a completed annotation session is shown below in Figure 17.

```
{
	"mediaID":"1091",
	"userID":"c51e7bf4-7406-4b4e-950b-92b7ef2e470f",
	"annotations":[
	{
		"annotationID":0,
		"datetime":"2016-05-31T11:09:28.6269095+00:00",
		"uv":[
			0.1096226,
			0.10108266
		],
		"value":1
	},

	....
}
```


Figure 17. Example JSON of coral cover elicitation point with location and annotation information.

An estimation technique is used to approximate the proportion of coral cover from the user annotated images. Due to the random scattering of annotation points for each session, the more times an image is annotated/elicited, the more accurate the estimate becomes. For 360-degree images, estimating coral cover using this annotation method is difficult due to the volumetric nature of the environment presented in the image. A preliminary, spatially random distribution approach was used in this project, but further research into different spherical sampling methods could be investigated that take into account the line-of-sight to coral, the water/benthic zone horizon line, and the overall structure of the coral bodies. Coral cover from 2D image annotations is much simpler to calculate, provided the photo is taken from the correct direction and distance from the coral, such as directly above the coral pointing downward.

2.1.4 Reef aesthetics survey

The aesthetics survey mode is a flexible approach to eliciting more qualitative information from users in a VR environment. After selecting and loading a reef image, users are asked to take a moment to look around and inspect the image, before then being asked a series of questions about the environment they have just examined. The use of immersive VR imagery for elicitation can translate into a better and more thorough communication of the scenario or environment that is being presented to the person being surveyed, and this can translate into more accurate elicitation results.

The survey session is initiated in the same way as the annotation mode; by selecting a reef location via the website map, and scanning the associated QR code. The image is then loaded and instructions are presented to the user asking them to examine the image in detail, before proceeding to the survey questions (Figure 18). At any time during the sequence of questions, the user can close the survey panel and re-examine the image without the survey interface occluding the image.

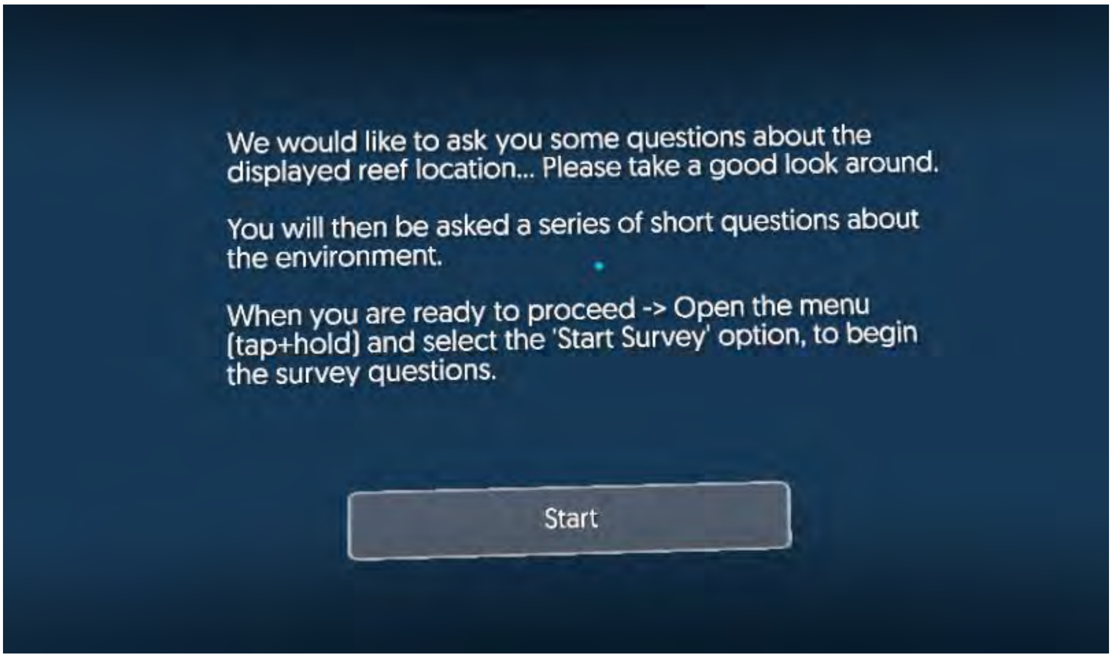


Figure 18. Reef aesthetics survey introduction screen.

The list of survey questions is requested from the REST service, in a similar way to the previous annotation procedure. JSON data is retrieved from the service which contains the full list of questions and available responses for each question. This information is used to dynamically build the survey menu panels within the VR application. Our approach provides the flexibility to add/remove/modify questions and responses at any time.

An excerpt of the JSON data format which is returned from the survey REST service query is shown below in Figure 19. Additional information is included such as question ordering, and help text to explain details and give the question context.

An example question retrieved is shown below in Figure 20. After each survey question, the user is asked to specify how sure they are about their answer to the previous question (Very Sure, Medium, Not Sure, Figure 21). This information is used to calibrate the user responses based on their level of confidence.

```
{
"Confidence":{
   "QuestionID":8,
   "QuestionHeading":"Confidence",
   "QuestionContent":"How sure are you of your previous response?",
   "QuestionHelpText":"Please give an indication of how certain you are of your response to the previous question",
         "QuestionOrder":0,
   "Answers":
         [
            {"AnswerID":3, "AnswerText":"Very Sure"},
            {"AnswerID":4, "AnswerText":"Medium"},
            {"AnswerID":5, "AnswerText":"Not Sure"}
         ]
},
"Questions":[
  {
    "QuestionID":1,
    "QuestionHeading":"Desirability",
    "QuestionContent":"Do you find this place visually pleasant?",
    "QuestionHelpText":"We’re interested in your personal appraisal regarding the beauty of the landscape that you are immersed in.",
    "QuestionOrder":1,
    "RequestConfidence":true,
    "Answers":
         [
            {"AnswerID":1, "AnswerText":"Yes"},
            {"AnswerID":2, "AnswerText":"No"}
         ]
  },
  {
    "QuestionID":2,
    "QuestionHeading":"Water Quality",
    "QuestionContent":"Is the image hazy?",
    "QuestionHelpText":"We’re interested in the visibility of the image. Can you discern clear outlines of the different objects that you observed. If these boundaries are disrupted in the background, the image is hazy.",
    "QuestionOrder":2,
    "RequestConfidence":true,
    "Answers":
         [
            {"AnswerID":1, "AnswerText":"Yes"},
            {"AnswerID":2, "AnswerText":"No"}
         ]
  },

….

}]}
```


Figure 19. Example of a JSON specification for the aesthetic questions.

Figure 20. Example survey question.

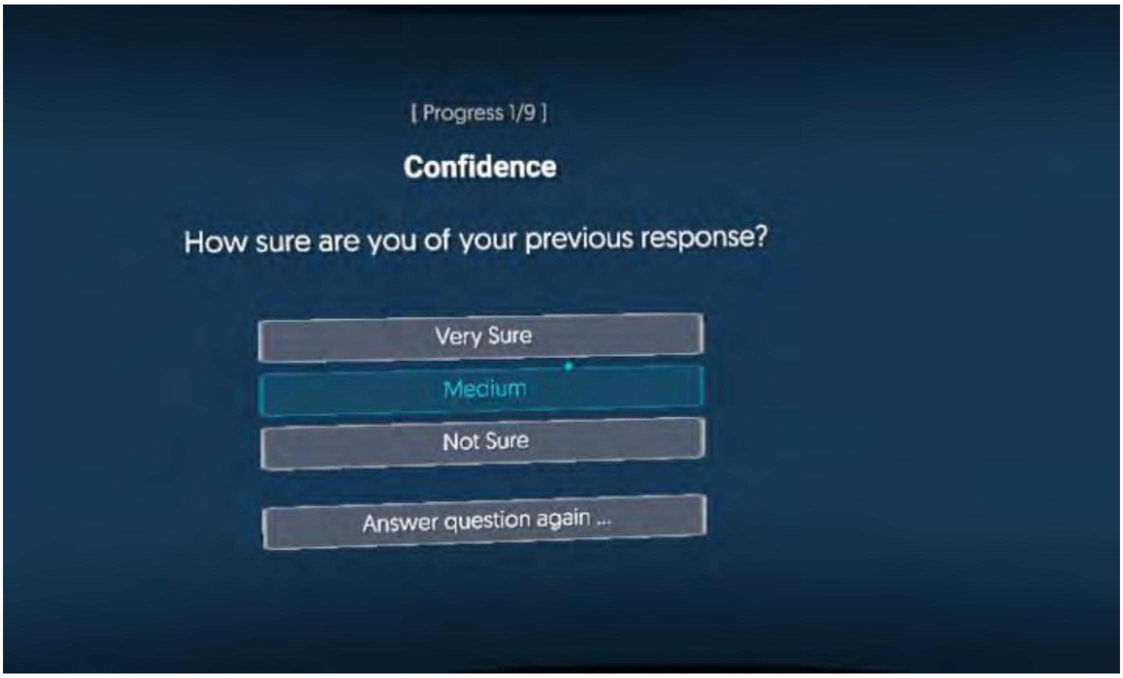


Figure 21. The user is asked to rate their confidence in their response to the previous.

Several experiments were conducted with users to test the effectiveness of the software, and to perform some initial analysis of survey results. The list of questions that were used are shown below. These questions require yes/no responses; however, the system is also capable of supporting more complex answers with greater than two options. More information on the experimental design for the Reef Aesthetics experiment is provided in Section 2.2.1.

- Do you find this place visually pleasant?
- Is the image hazy?
- Do the live corals on the reef form structurally complex habitats?
- Can you see evidence of damage to the reef?
- Is the reef mostly one colour?
- Can you see individual fish?
- Do you see schools of fish?
- Do you see more than one type of fish?
- Can you see other organisms than corals and fish?

2.2 Applications

2.2.1 Coral cover annotations

Elicitation applications were used into two modelling applications. In the Coral Cover Model, citizens used a 2-D elicitation application to annotate images and predictive models were fit to the coral cover proportions that were produced. In the Reef Aesthetics experiment, citizens, experienced scuba divers, and marine scientists were interviewed using the VR application, which they used to view 360-degree images. A description of these two applications is provided below.

2.2.1.1 Reef Check image extraction

Reef Check Australia (Reef Check; http://www.reefcheckaustralia.org/) is a citizen science organisation working to monitor the Great Barrier Reef. Reef Check recruits and trains volunteer divers to perform underwater visual reef surveys. The citizen science images used in this project were extracted from video surveys undertaken by Reef Check.

A selection of 13 DV tapes, representing videos of reef surveys from Magnetic Island to Osprey Reef, from 2003 to 2009, were converted to video files. The files each contained between 25 and 120 minutes of video, which were broken up into multiple sites, which in turn were broken up into 4 transects. At the beginning of each site survey, the diver indicated which transect was being surveyed by holding up fingers or a slate with the same information. Each video was manually searched for transect start and end points and the timestamps were recorded in a spreadsheet. These entries were also matched with a counter number, a reef name, a site number and the coordinates of that reef using a metadata table provided by Reef Check.

Images were extracted from the videos by pulling out frames at set times. For each transect, 1000 timestamps were generated from a 1D Poisson point process, between the start and end times of that transect, and 5 of these timestamps sampled while ensuring that at least 10 seconds had elapsed between them; thus ensuring that the same area was not present in consecutive images. After extraction, images were deinterlaced and an unsharp mask applied in Adobe Photoshop CC 2015 in order to provide an image free from distortion. The position of each image was estimated based on the timestamps of the sampled frames, and information about the start position and bearing of the transects. This provided a way to locate and display each image on a map.

2.2.1.2 Annotation of Catlin images

A training set of 20 XL Catlin Seaview Survey images (González-Rivero et al. 2014) was used to assess 12 volunteers' ability to accurately identify coral within the 2D elicitation module. Access to citizen elicitors was limited during this stage of the project, and so the "citizen scientists" were made up ofo 6 team members and 6 Reef Check volunteers. Prior to annotating images, citizens were asked to read through a training document, which highlighted the differences between hard coral, soft coral and other morphologically similar organisms. The accuracy of each citizen's coral cover estimates across the 20 images was assessed based on annotations provided by a marine scientist and used to determine a citizen-specific weight representing user annotation accuracy.

The average classification accuracy of citizens compared to the marine scientist was 0.8 (Figure 22). This suggests that the citizens were more often than not correctly identifying image features which were, and were not corals. The variability in the accuracy levels across the 20 images was relatively large, but consistent for the 12 citizens (Figure 22). This variability is likely attributed to image properties and the benthic composition; the 20 Catlin images used in the training set were selected to capture a wide variety of reef characteristics, such as haziness, sand, and soft and hard corals and these characteristics increased or decreased the users' ability to accurately classify coral.

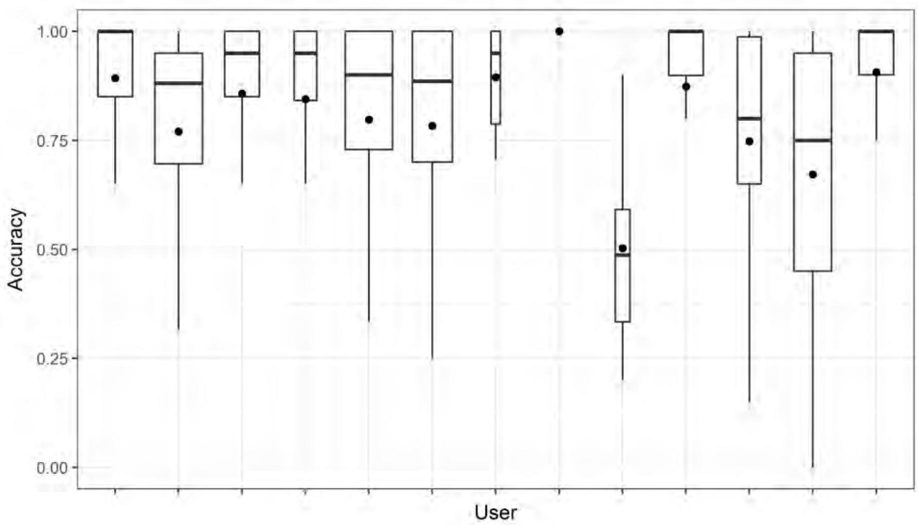


Figure 22 Accuracy of coral cover estimates obtained from Citizen Users compared to those of a marine scientist (whose accuracy is shown as 1). Black dots denote a user's mean accuracy across all images they annotated, and the width of the boxplot is proportional to the number of annotations performed.

2.2.1.3 Annotation of Reef Check images

The 12 citizen scientists were asked to annotate 218 Reef Check images using the 2D elicitation application, after re-familiarising themselves with the training document. This resulted in 1758 whole-of-image annotations and 34969 individual point annotations. The images were selected from 8 reefs, which were targeted because they were collected in areas, or at times, where professional monitoring data were either not available, or sparse. The annotated Reef Check images were included in the regression modelling, with individual accuracy weights assigned to each citizen, as derived described above.

2.2.2 Reef aesthetics survey

In this experiment, the VR elicitation tool was used to learn about the GBR's reef aesthetic value. Our main goal was to gain knowledge about the perception of reef beauty to help managers and conservationists better assess reef aesthetic value. The GBR was listed as World Heritage Area in 1981 and is widely recognized for containing superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance (Criterion vii). That is, under the World Heritage Convention, the Australian federal and Queensland state governments have a responsibility to monitor and report on the GBR aesthetic values, as well as more traditional ecosystem-health measures such as water quality and biological diversity. A large number of visual criteria have been evaluated as part of GBR aesthetic value assessment in an effort to identify attributes that embody the values described in Criterion vii (Johnston et al. 2013). However, previous studies have shown that this methodology cannot be used to capture non-visual criteria and as a result, the sensory experiences are not considered in the assessment of the GBR aesthetic values (Lucas et al. 1997, Pocock 2002, Johnston et al. 2013).

We interviewed three groups of people with different links and experiences with coral reefs: 1) the Marine Scientist group, which consisted of reef experts with strong links to the GBR; 2) the Experienced Diver group, who have experienced the underwater environment; and 3) a Citizen group, where participants have only seen the GBR through documentaries and images. Each participant elicited 5 360-degree images showing different underwater reefscapes from the GBR and answered questions about their visual and emotional perceptions. A Bayesian hierarchical model was used to quantify aesthetic indicators, which explained the perception of an aesthetically pleasing reef and provided insights about relationships between past experiences and a sense of beauty.

2.2.2.1 Images and survey design

A total of 39 360-degree images collected throughout the GBR in 2012 were provided by the XL Catlin Seaview (Gonzalez-Riviero 2014) and used in the study. Images were selected across a range of attributes hypothesized to describe aesthetic value within the GBR. These included the coral cover and structural complexity, coral health, colour diversity, damage to corals, fish abundance and diversity, as well as visibility. We then developed an experimental design that ensured that each participant was shown a subset of images that captured the variability in visual attributes within the 39 images. Each participant started with the same "training image", which was selected because the image attributes fell into the medium range. Then they were taken through the elicitation process with four additional images selected using the methods described above (Report 4/4 – Modelling document).

2.2.2.2 Survey questions

We selected a set of visual underwater indicators, which were chosen based on key factors adopted to assess GBR aesthetic value (Johnston et al. 2013). Below the water, reef aesthetic values are typically described by water clarity, the variety of shapes and forms of corals, shells and fish, marine life abundance, diverse colours and an additional "wow" factor such as the presence of large marine creatures (i.e sharks, turtles, dugongs, whales, etc.). We used this knowledge to prepare 9 questions with Yes and No answers in a non-technical language to be comprehensible by the three groups. The questions were:

Q1. Do you find the image visually pleasant?

Q2. Is the image hazy?

Q3. Do the live corals on the reef form structurally complex habitats?

Q4. Do you see evidence of damage to the reef?

Q5. Is the reef mostly one colour?

Q6. Can you see individual fish?

Q7. Can you see schools of fish?

Q8. Can you see more than one type of fish?

Q9. Do you see any organisms other than corals or fish?

For each of the 9 questions, the participant was also asked about the certainty associated with their answer (i.e. very sure, sure, and not sure).

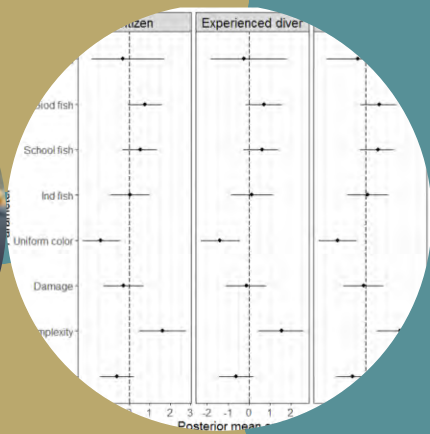
2.2.2.3 Survey participants

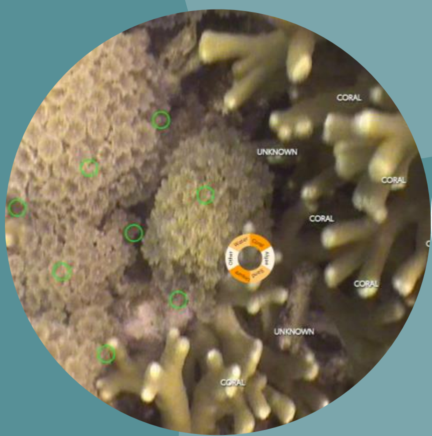
Elicitations were performed by 4 interviewers at several locations in Queensland from the end of September to mid-November 2016. For the most part, Marine Scientists were interviewed at the Australian Institute of Marine Science, the GBR Marine Park Authority and the University of Queensland (UQ) Global Change Institute. Participants in the Experienced Divers group were members of the UQ scuba-diving club "Unidive", while Citizens were interviewed as part of the ReefBlitz event in Brisbane and at QUT.

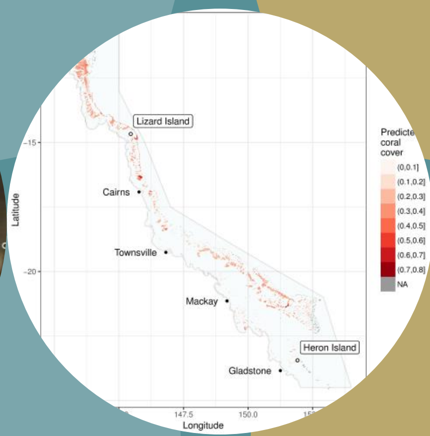
A total of 105 participants were interviewed who represented a range of ages (18 to >45), gender, and scuba-diving experience levels. The largest number of participants belonged to the Marine Scientist group (37 participants), followed by the Citizens (36 participants) and the Experienced Diver group (32 participants), respectively.

3. Modelling


Run-off
Sediment
Nutrients
Bathymetry
Turbidity
Chlorophyll
Disturbances
Secchi depth
Take/No Take Zones
Light extinction
Coral cover


Experienced diver
School fish
Ind fish
Uniform color
Damage


CORAL
UNKNOWN
CORAL
CORAL
CORAL
UNKNOWN
CORAL


Lizard Island
Cairns
Townsville
Mackay
Heron Island
Gladstone
Latitude
Longitude
NA

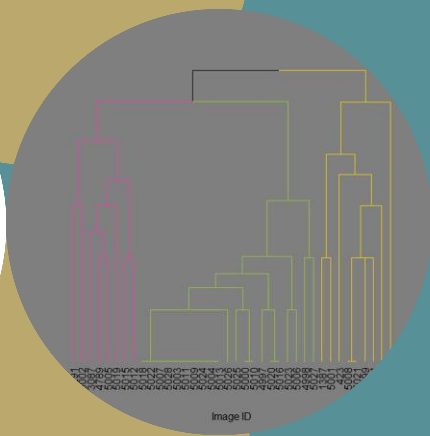


Image ID

3.1 Coral cover model

A major aim of the Monitoring Through Many Eyes project was to create a predictive visual environment to better monitor the health of the Great Barrier Reef (GBR). We combined crowd-sourced imagery with existing spatial information products and employed advanced spatial-temporal statistical models to predict coral cover throughout the GBR.

3.1.1 Summary of input data

We modelled coral cover data from a number of different sources including the: XL Catlin Seaview Survey (Gonzalez-Rivero et al. 2014); Great Barrier Reef Long Term Monitoring Program (LTMP) and the Reef Rescue Marine Monitoring Program (MMP), conducted by the Australian Institute of Marine Science (AIMS); the Heron Island survey and the Capricorn and Bunker group survey conducted by the Remote Sensing Research Centre (RSRC) at the University of Queensland (UQ). Each dataset provided multiple estimates of coral cover, but there were differences in the scale of the estimates and the estimation method (Table 1).

Table 1. Differences in the coral cover data source included the scale of the coral cover estimate, the number of images the estimate was based on, the extent of each individual image, the classification method, and the number of annotations per image.

Source	Number of reefs	Scale	Number of images	Image extent (m^2)	Classification method	Annotation points
Capricorn and Bunker group	13	Image	1	4.00	Annotated	24
Heron Island	1	Image	1	4.00	Annotated	24
XL Catlin	32	Image	1	2.00	Automated	100
LTMP	47	5 × 50m transects	40	1.00	Annotated	5
MMP	32	5 × 20m transects	32	1.00	Annotated	5
Reef Check	60	Image/person	1	0.12	Annotated	20

3.1.2 Reef reference raster

A reference raster with a spatial resolution of 0.005 decimal degrees (dd) was created, covering the extent of the reefs in the GBR. The GBR Features shapefiles (GBRMPA 2014) were used to identify reef areas within the GBR, which were buffered by 1km and converted to raster format. The resulting reference raster was then used to aggregate and align other covariate rasters. The resolution of 0.005 dd was chosen as it was comparable to the existing resolution of the covariate rasters and produced a reasonable cell count for modelling and visualisation (85529 cells). Please see Report 4/4- Modelling for a full description of the reference raster and covariate data sources.

3.1.3 General model description

A number of physico-chemical, topographic and disturbance variables were included in the model to account for direct and indirect sources of variation in coral cover (Figure 23). In addition, GBR Management Zones and Marine Bioregions from the Great Barrier Reef Marine Park Authority (GBRMPA) have been used to account for, respectively, North-South gradients in coral cover and the difference between inshore- and outer-shelf coral cover (GBRMPA, 2014).

The sparsity of the data in some zones and bioregions of the GBR have been accounted for by combining the Far Northern and Cairns/Cooktown Management areas together. For the same reason, all bioregions in the Southern part of the GBR were combined as "Outer", resulting in a total of seven geographical regions potentially accounted for in the model.

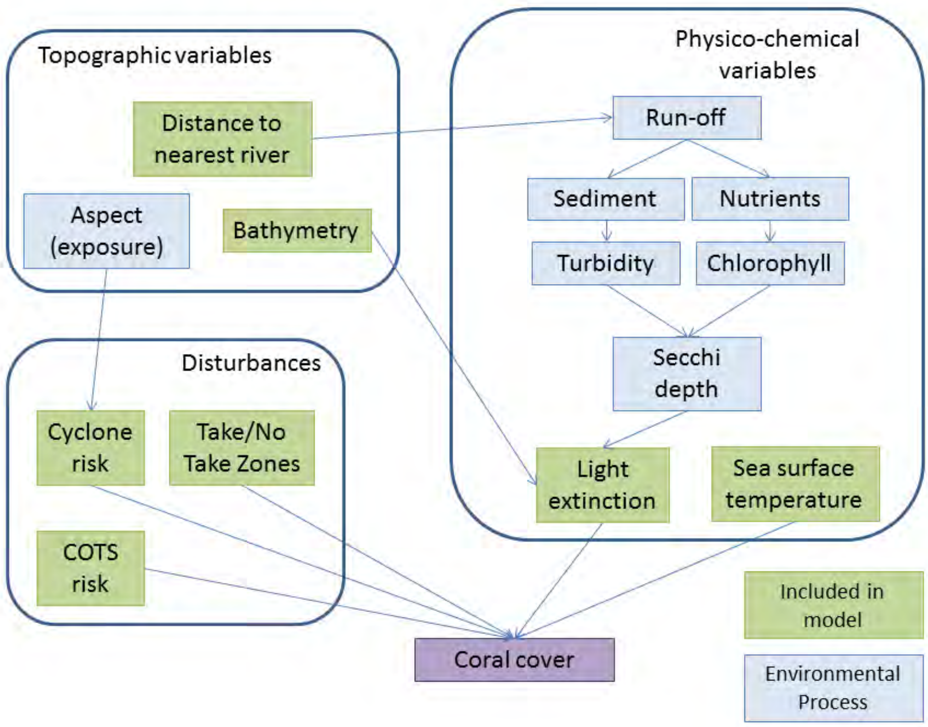


Figure 23. Conceptual model showing the direct and indirect influence of variables on coral cover.

The proportion of coral cover, $\bar{y}_{its}$, at cell s_i, from source s, and time t was modelled using a generalised additive model (GAM) in the mgcv R package (Wood, 2011) to account for the effects of the physico-chemical, topographic and disturbance covariates, a temporal trend, and a spatial random effect. Coral cover estimates were derived using mechanistically motivated weights that were designed to account for the different types of data (i.e. professional vs. citizen survey) and several image-quality characteristics, including the image extent, number of images per coral cover estimate, number of annotations, and annotator accuracy. Then, coral cover estimates were aggregated to the 0.005 dd scale, by source, for use in the modelling. A detailed description of the weights, the spatial aggregation of data, and the model can be found in the Report 4/4 – Modelling document.

We fit the model to two separate datasets to highlight differences in model predictions when a model is fit to data from multiple sources, as described above. First we fit the model to all of the data available (i.e. LTMP, MMP, Capricorn and Bunker, Heron, Catlin, and Reef Check) and used the methods described in Report 4/4 to weight the data; we refer to as the "All data" model. Then we fit a model to the LTMP and MMP data only, which did not include a weighting scheme to account for differences in the data sources; we refer to this model as the "LTMP/MMP" model. We assessed the predictive ability of the models based on the coverage of 80% prediction intervals, the mean squared error (MSE), and the median absolute deviation (MAD) of the observed versus predicted values. These statistics were calculated both with and without the weighting scheme, to account for the relative importance of the observations in the model fitting. That is, observations with large weights were considered to contribute more to calculations of the MSE, MAD and 80% coverage. This allowed us to highlight differences in the model predictions within a region where LTMP and MMP routinely sample.

3.1.4 Results

3.1.4.1 GBR scale coral cover model

A total of 1735 spatially aggregated coral cover estimates were used to model the proportion of coral cover for the entire GBR between 2002 and 2016. The covariate effects on coral cover in the All data model tended to reflect what we expected, given our conceptual model (Figure 23). Light extinction and the presence of a no-take zone had a positive effect on coral cover. After accounting for the positive effect of light, depth had a negative effect on coral cover. Surprisingly, there tended to be less coral on the middle and outer shelves compared to the inner shelf. However, this was after accounting for the spatial random effect and so some of the spatial variability was likely described by the reef clusters.

The spatio-temporal model accounted for changes in coral cover across the GBR in both space and time. Coral cover was predicted to be the highest (approximately 0.8) on the inner reefs near Bowen (between Mackay and Townsville) and lowest near Townsville (Figure 24). However, this region was also associated with the highest prediction uncertainty, as very few reefs were sampled in this area. The predictions with estimates of uncertainty can be seen on the "Explore" map of our website (see Section 1.4) and in Figure 24.

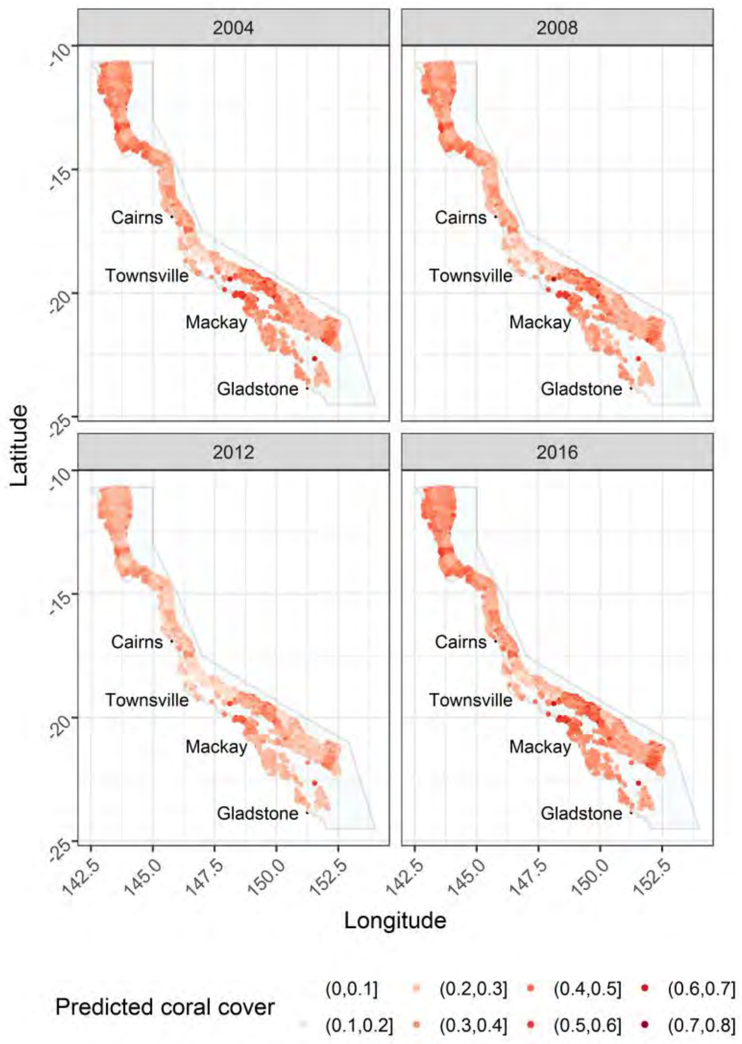


Figure 24. Predicted coral cover across the Great Barrier Reef Marine Park (blue polygon) for 2004, 2008, 2012 and 2016 for the model of the GBR as a whole. Major coastal cities are shown as black points.

Overall, the coral cover at the GBR scale decreased markedly over the period 2008-2013 before beginning to recover (Figure 25). These changes correspond to the cyclones Hamish (2009), Yasi (2011) and Ita (2013) that affected a large part of the GBR. Note that data collection in 2016 occurred prior to that year's mass coral bleaching event.

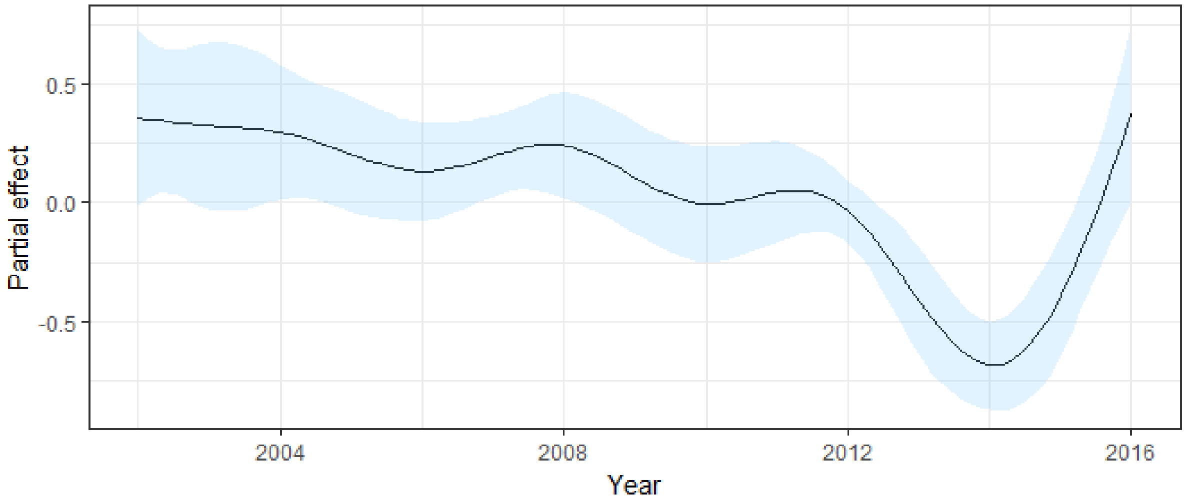


Figure 25. Partial effect of temporal random effect on logit of coral cover from the spatio-temporal model of coral cover (2002-2016).

3.1.4.2 Effect of including multiple data sources

We compared the predictions from the two models at the whole-of-the GBR scale and found that the weighted MSE for the All data model was 0.016 (unweighted MSE = 0.014) and the weighted MAD was 0.081 (unweighted MAD = 0.073). This indicates that while the model did not capture all of the spatio-temporal variability, it was able to capture trends across the GBR (Table 2). The weighted 80% prediction interval coverage was 83.3% and the unweighted 80% coverage was 81.4%. Although this is slightly wider than anticipated, it does not suggest there is a problem such as overly confident predictions centred around a poorly estimated mean.

Table 2 Model diagnostics (unweighted and weighted) for predictions Great Barrier Reef from models using all the data available and only the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) data.

Model	Coverage	80% Coverage Weighted	MSE	MSE Weighted	MAD	MAD Weighted
All data	0.812	0.823	0.016	0.014	0.081	0.074
LTMP/MMP	0.802	0.740	0.015	0.018	0.075	0.088

Next, we focussed in on the predictions from the Capricorn and Bunker group of reefs, including Heron Island, because it is an area where LTMP and MMP data are available along with numerous other data sources, which are not repeatedly measured on an annual or biennial basis. The coral cover predictions produced by the All data model were lower in the Capricorn and Bunker region than the predictions produced by the LTMP/MMP model (Figure 26). In addition, the logit-transformed standard deviations of the predictions for the All data model were approximately half that of those produced by the LTMP/MMP model, and there was more spatial variability in the uncertainty estimates (Figure 27). These results suggest that fitting the model to the full dataset provides greater certainty about the predicted values in these reefs, as well as finer-scale information about the spatial variability in those certainty estimates. Finally, model diagnostics for predictions made in the Southern Zone indicate that the All data model were more accurate and have better prediction coverage than the LTMP/MMP model (Table 3).

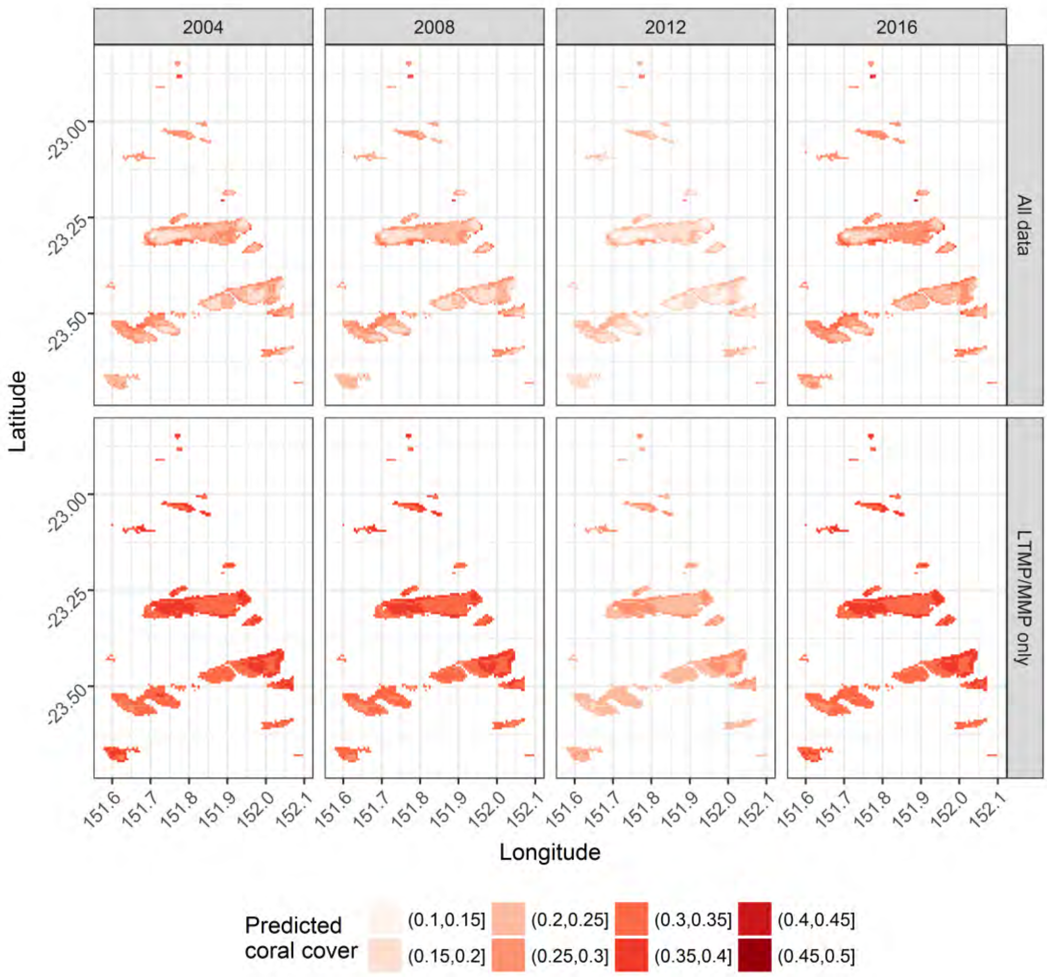


Figure 26. Predicted coral cover in the Capricorn and Bunker group of reefs from a model fit to all of the data sources (All data) versus another model fit to the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) data only.

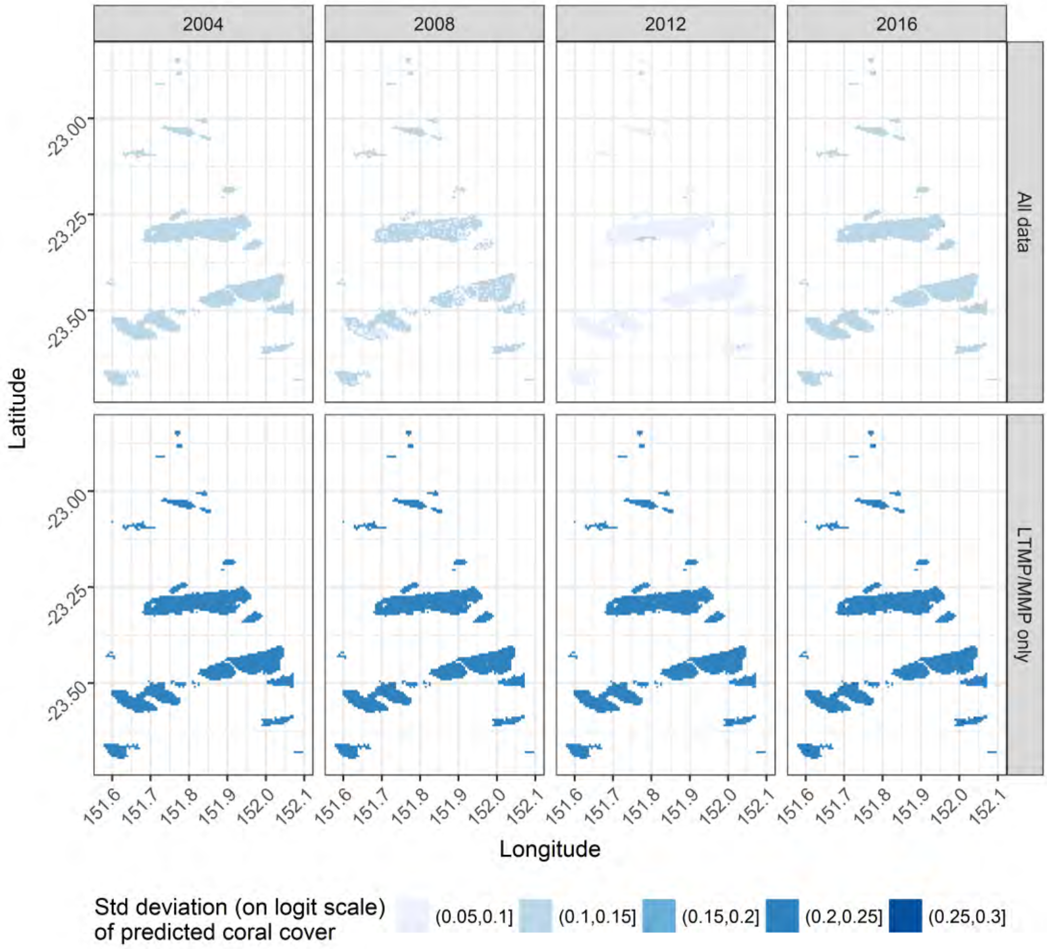


Figure 27. Prediction standard deviations (on the logit scale) of coral cover in the Capricorn and Bunker group of reefs from a model fit to all of the data sources (All data) versus another model fit to the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) data only.

Table 3. Model diagnostics (unweighted and weighted) for predictions in the Southern Management Zone of the Great Barrier Reef from a model fit to all of the data sources (All data) versus another model fit to the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) only.

Model	**Coverage**	**Coverage Weighted**	**MSE**	**MSE Weighted**	**MAD**	**MAD Weighted**
All data	0.681	0.736	0.024	0.016	0.095	0.078
LTMP/MMP only	0.613	0.549	0.026	0.029	0.112	0.122

3.1.5 Discussion

It is critical that all of the data currently available is used to monitor and manage the GBR. In this study, we demonstrated how data from multiple sources, such as professional monitoring and citizen science data, can be combined within a single statistical model and used to make predictions, with estimates of uncertainty, throughout the GBR and over time. At the most basic level, differences in prediction uncertainty help managers understand where they can be most, or least confident in the predictions. This could be used to prioritise management actions, or identify areas where additional information is needed before management actions are implemented. The estimates of uncertainty can be shared between organisations, so that sampling across the expanse of the GBR can be better coordinated to engage citizen scientists in the ongoing collection and annotation of images. Although we used coral cover as an example, this general approach is equally viable for other variables collected in the marine environment, as well as in other ecosystems.

The modelling framework we developed includes a mechanistically based weighting scheme that accounts for the differences in survey design and coral-cover estimation method, as well as the inherent quality of the images. This provides a way to integrate coral cover estimates derived from citizen-contributed images and citizen annotations of hundreds of images, while still accounting for differences in the quality of citizen science data compared to professional survey data. The approach is scientifically and statistically appealing because not all surveys are created equally. In addition, more data are available to fit the model and this results in an overall increase in information about coral cover throughout the GBR. In this particular case, the model results suggest that including additional data sources (e.g. Catlin, Heron Island, Reef Check and Capricorn Bunker), in addition to the LTMP and MMP, resulted in a 22.2% reduction in uncertainty based on the weighted MSE. Although, the effect of incorporating additional data on the model's predictive accuracy is expected to vary spatially and temporally depending on the density of existing data nearby (in space and time), as well as the source and quality of the new data being integrated.

The relationships between coral cover and the covariates in the spatio-temporal model tend to reflect what we expected based on our ecological understanding of coral cover. However, few of the influential drivers in the conceptual model (Figure 23) were significant in the final model. This is not surprising because the modelling framework currently makes use of static covariate raster layers. At present, temporally dynamic layers of disturbances such as COTS, cyclones, disease outbreak, and bleaching are not available, but these layers are currently under development (Pers. Comm., C. Mellin). The inclusion of these data in the model should increase our ability to predict temporal variations in coral cover resulting from disturbances. In turn, the temporal random effect would identify changes over time that could not be attributed to these covariates.

The citizen science data currently has little weight in the model compared to the professional survey data, due to the small pool of 'citizen scientists' and citizen-contributed images in this pilot study. However, additional elicitation of images will provide extra weight to the existing citizen-science based coral-cover estimates, as well as additional spatio-temporal data coverage. A discussion about how to account for image quality in the weights is included in the Report 4/4 – Modelling document.

3.2 Reef Aesthetics model

The Reef Aesthetics model was formulated to estimate the probability that a participant found the reef aesthetically pleasing, which corresponds to the answer for the interview question, "Do you find this image visually pleasant?". The answers to the remaining questions described in Section 2.2.1.2 were used as explanatory variables in the model.

3.2.1 Summary of input data

On average, the participants found most images aesthetically pleasing. At the group level, the Experienced diver was most likely to answer yes, while the Citizen group had the highest proportion of 'no' responses. Questions regarding the visual aesthetics indicators were answered with different levels of certainty across images. Figure 28 shows the proportion of responses, across all groups, for each question and image. For some images, most participants agreed on each question. For example, the training image 4996 encompassed all possible responses whereas the proportion of Yes with high uncertainty (YesH) response was maximum for most of the questions on the image 5022. For image 3097, in contrast, participants did not all agree that the image was aesthetically pleasing. Overall, the detection of individual fish (Q6) and schools of fish (Q7) with a high level of certainty (YesH) were the two most common responses across all groups and images.

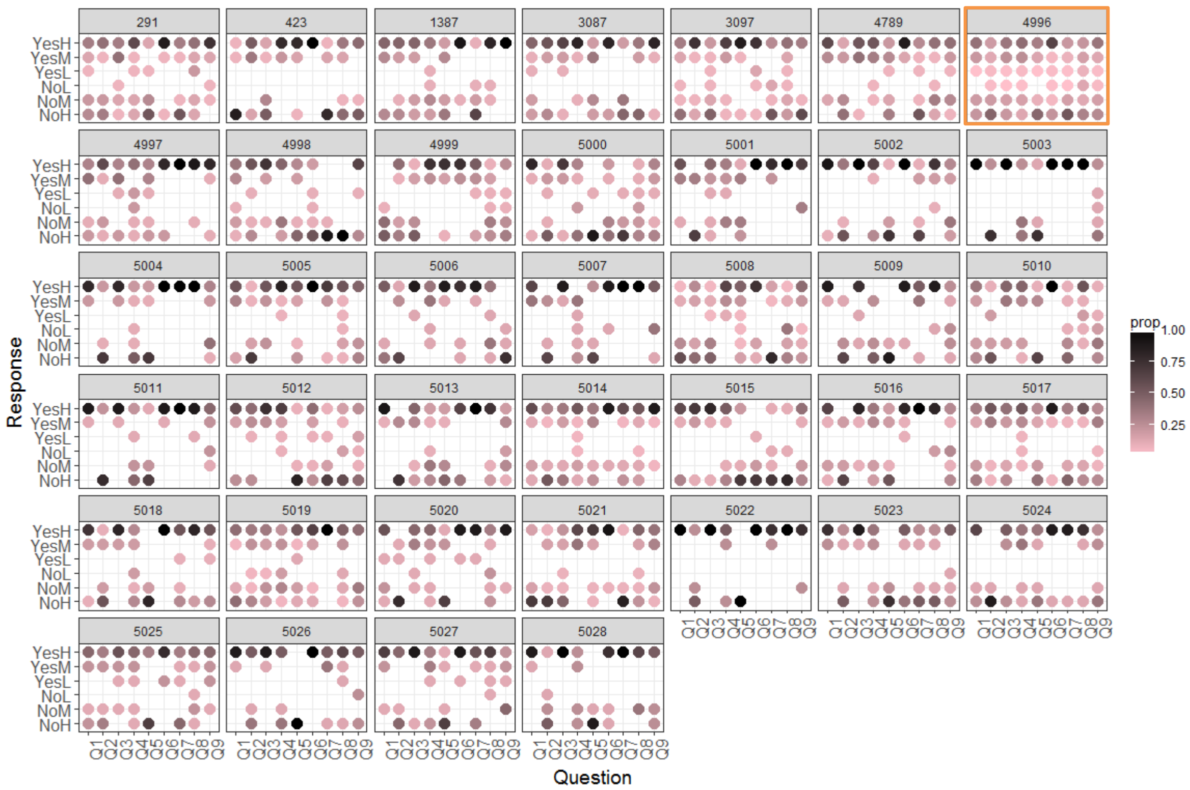


Figure 28. The proportion of responses to the entire interview questions described in Section 2.2.1.2 The image with the orange box around it was the training image.

3.2.2 General model description

As mentioned previously, the purpose of the model is to identify the relationship between an aesthetically pleasant reef, nine different attributes elicited from participants, and demographic information (Table 4). A Bayesian hierarchical model was used to estimate the probability that a reef is aesthetically pleasant as function of questions *k*, images *j*, groups *g* and different levels of uncertainty *s* formulated in a hierarchical fashion. A detailed description of the model can be found in the Report 4/4 – Modelling document.

Table 4. Covariates considered in the Reef Aesthetics model.

Covariate name	Description
Demographics	
Group	Participant belongs to the Marine Scientist, Experienced diver or Citizen group
Gender	Gender of the participant
Young	Participant younger than 26 years of age
Old	Participant older than 45 years of age
Dive occasionally	Participant that dives occasionally, less or equal to one time per year
Dive often	Participant that dives more than one time per year
Aesthetics Interview	
Q2. Hazy	Water quality - Is the image hazy?
Q3. Complexity	Structural complexity - Do the live corals on the reef form structurally complex habitats?
Q4. Damage	Damage on the reef - Can you see evidence of damage to the reef?
Q5. Colour	Colours – Is the reef mostly one colour?
Q6. Individual fish	Biodiversity - Do you see individual fish?
Q7. School of fish	Abundance - Do you see schools of fish?
Q8. Fish biodiversity	Biodiversity – Do you see more than one type of fish?
Q9. Biodiversity	Biodiversity - Can you see organisms other than corals or fish?

3.2.3 Results

Model predictions were classified into three groups that included a high, medium, and low probability of being visually pleasant. Most images that fell into the high probability class were found in the northern part of the GBR (see Report 4/4- Modelling document); although low and medium classes were found across the entire GBR. The class with a medium probability of being aesthetically pleasing included 19 reefs, while the low and high classes contained 10 reefs each. The highest probability that an image is aesthetically pleasing was 0.95 for the image 5028, while the lowest was for image 4999, with 0.17 (Figure 29). Image 5028 is from a cluster characterized by high colour diversity, abundant fish, high coral cover without apparent damages and high levels of structural complexity and visibility. Image 4999 is characterised by low to medium structural complexity, poor to medium visibility, and low coral cover (see Report 4/4 – Modelling document).

A Bayesian hierarchical linear model was developed (Gelman et al., 2013; Plummer, 2016) to investigate which of the aesthetic features were associated with a perception of a reef being aesthetically pleasing.

In total, two aesthetic indicators were found to be significant in the model. The structural complexity question (Q3) was positively associated with perceived aesthetic value, while the question relating to reef colour (Q5) was negatively associated with aesthetic value. Note that a negative response to the colour question indicates that the reef is not uniform in colour (Figure 29), which suggests that participants perferred colourful reefs. The model also estimated (Figure 30) negative effects of Haziness (Q2), Damage (Q4) and Biodiversity (Q9) and positive effects of fishes (Q6-Q8). However, the 95% credible intervals for these parameters included 0 and so these results are not substantive.

Figure 29. Equirectangular projection images of the most and less aesthetically pleasing image (top and bottom panel, respectively). Copyright XL Catlin Seaview survey, see 360-images at the links: http://globalreefrecord.org/transect_explorer/12026/image/120261897/threesixty, http://globalreefrecord.org/transect_explorer/12035/image/120351218/threesixty

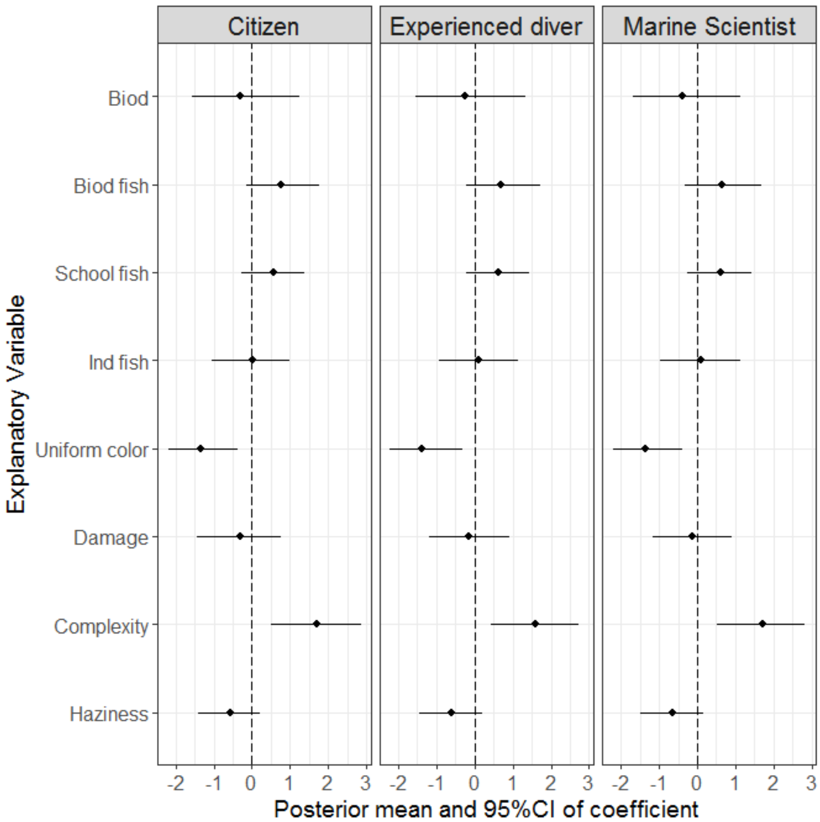
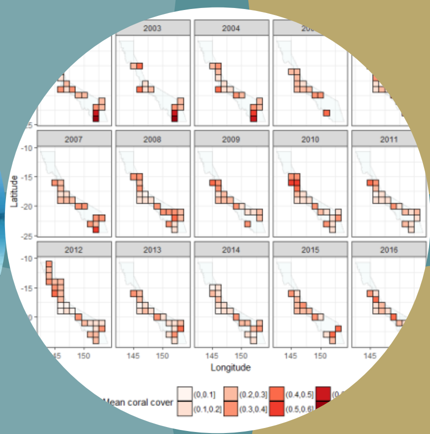


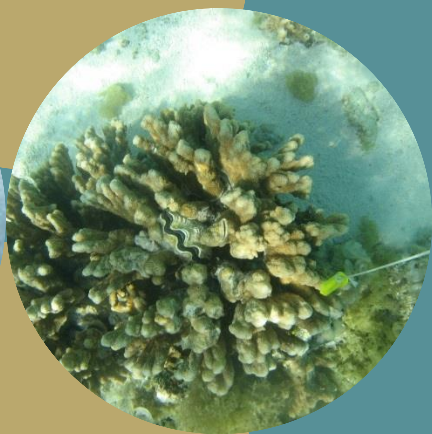
Figure 30. Statistical summary of model coefficients for each of the explanatory variables estimated by the reef aesthetic model, by group.

3.2.4 Discussion

The use of virtual reality provides an innovative way to tap into the human experience, allowing us to learn more about the particular characteristics that make a reef beautiful. In our experiment, we quantified the effects of nine reef-aesthetic indicators and used them to identify reef characteristics that people perceive to be aesthetically pleasing. We found that the structural complexity indicator and diverse colours strongly influence people's perception of a beauty. Surprisingly, no statistically significant differences were found between the three groups of participants. This finding suggests that a person's past experiences in a reef environment do not directly influence their perception of the beauty. Interestingly, structural complexity is a reef-heath indicator (Mumby and Steneck 2008). Marine Scientists would be aware of this and therefore, their perception of the beauty may have been linked to what they perceive as a healthy reef; in fact, the language used by the Marine Scientists suggested this during the interviews. However, Citizens and Experienced divers would be less likely to know what contributes to reef health, yet they also deemed structurally complex reefs as visually pleasing. Thus we believe that structural complexity is both an indicator of aesthetic value, as well as reef health. In contrast, the diversity of colours is not monitored during reef-health surveys. Therefore, including an assessment of reef aesthetic indicators related to colour would add an important additional dimension to management and conservation efforts in the GBR.

4. Workflow Management





4.1 Software Architecture

There are 3 main components to the software architecture for this application, viz. Modelling, Elicitation and Visualisation (**Error! Reference source not found.**32). These have been described functionally in the previous sections. The diagram below shows the relationships between software modules and general data flows. The diagram also lists technologies required for implementation as a brief manifest.

The *citizen inputs* as images and meta information are stored in the database upon upload by contributors. This image information is utilised by the *Expert Elicitation* application to extract expert knowledge of coral cover and aesthetics, which are then stored in the same *Data Storage* model. The *Modelling Module* takes this data and generates the Coral cover prediction and error images that can be shown in the *Visualisation* as a Cesium map. Readers are directed to the Implementation Manual situated within the source code repository for detailed system development and implementation details.

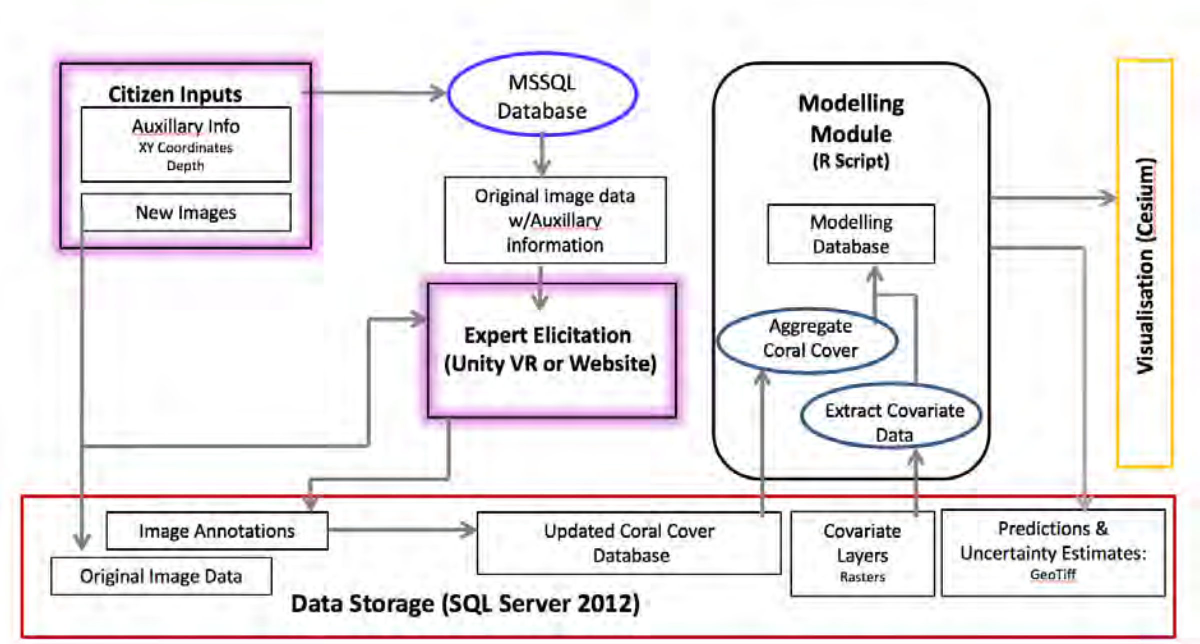


Figure 31. Overall software architecture diagram

Software Technology Manifest to implement the prototype system:

- Windows Server 2012 R2 VM - overall OS environment executing web and modelling system components;
    - Internet Information Services v8.0 (IIS) hosting implements website described in Chapter 1;
    - ASP .NET 4.5 - support;

    - SSL Certificate - for secure exposure of the website to external access, provided by QUT for live website.
- Unity Application – VR Viewer implementing expert and non-expert elicitation functionality described in Chapter 2;
- R V3.3.2 Scripting modules - to implement modelling components described in Chapter 3; and
- Relational database – SQL Server 2012 providing data storage services.

We now describe how these services are integrated to form an extensible service architecture. In particular, we describe the RESTful services and Database components supporting the prototype system.

4.2 RESTful Services

Core data interactions for website occur through a RESTful interface, supplied in both JSON and CSV format where required, as described in previous sections of the report.

This RESTful endpoint is built using Microsoft Web API framework in conjunction with the Entity Framework to communicate with MS SQL Server. This provides data interactions through a JSON data service, delivered over the HTTP protocol, which can be consumed easily by web applications (Chapter 1) and the VR application (Section 2.1).

Communication between the website and VR application is performed through REST API calls created with the Microsoft.Net WebAPI v2 in a web forms based ASP.Net 4.5 website environment. Interactions with the user interface utilise these REST services, along with JQuery and Cesium 3D mapping frameworks. Both frameworks are open source.

4.3 Database

The database behind the website, modelling framework and VR application is all contained within a Microsoft SQL Server database. Currently both the internal fully featured prototype application and the publicly accessible website will use the same database, located within the QUT SQL Server cluster. An empty database will be supplied as part of the software deliverable package, along with instructions on how to populate the empty database with available model data licenced by users of our system.

The database is currently hosted on Microsoft SQL Server Enterprise Edition (64-bit), on the internal QUT server **SQLQUT01-DEV**. The database is named "**IFE_GBREEF_DEV**" and it contains the traditional Microsoft Identity tables for Membership provision. These tables are all prefixed with AspNet and are not featured in the database architecture diagram below, as they are independent of the customised data structure created for this application. The relationship to the membership provider and the customised table is maintained through the UserID field, which is unique to each user account.

Access to the database is through a SQL Server identity, passed through the web.config file in the ASP.Net application. The entire data structure is maintained through the Entity Framework instance on this connection, created and served within the website framework. The database table design and relationships can be seen in Figure 32.

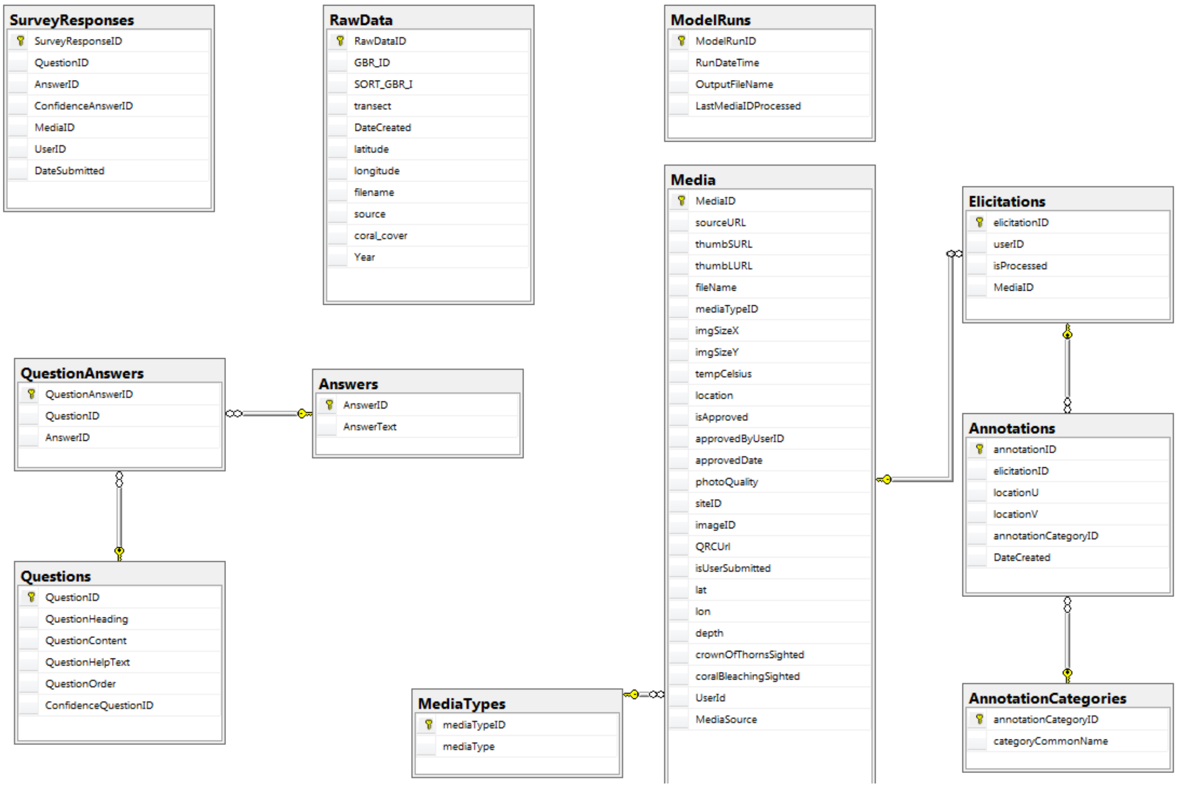


Figure 32. Database tables for prototype system.

Discussion

The Monitoring Through Many Eyes project demonstrates the promising capabilities of our software platform. Major components include website integration, VR elicitation, modelling, and an underlying workflow framework. The platform can be used to engage and raise public awareness about the condition and management of the Great Barrier Reef, but it also represents an innovative new approach to monitoring the reef.

First, web-based users can explore the citizen-contributed images, help classify those images, and be a part of the active modelling and management of the reef. These exciting citizen engagement opportunities have been explored with 360-degree cameras and accessible virtual reality viewers, which allow citizens to immersively experience the reef and provide annotations of the images that contribute directly to the monitoring effort. This provides a powerful user experience aligned with our work that will encourage people to continuously contribute as an online community.

Both VR and 360-degree video technology is becoming more affordable for household and business budgets. Our project contributes a novel next-generation immersive VR tool that utilises situated cognition theory to elicit more accurate expert knowledge using citizen-sourced 360-degree and 2D images. We have exploited these opportunities in our prototype to offer a new way of using VR in citizen science, to capture knowledge and not just to provide a user experience. Such a VR approach is well poised to exploit the proliferation of such technology and to provide high-quality citizen-science data for future modelling projects. In addition, this platform can be further improved with community creation and gamification aspects that is expected to increase the number of people contributing, as well as the quality of data, due to the user-motivation engendered to succeed in the related online community.

Secondly, thousands of underwater images are taken by visitors each year, and harnessing this new source of citizen-sourced data will substantially increase information about reef health. These new data are much less costly to collect than traditional monitoring data, and can provide additional information about reef status and trend; potentially in real time so that managers can respond quickly to disturbances. Statistical models can also be re-fit as new data comes in, providing up-to-date predictions of reef health, with estimates of uncertainty, in areas where information was previously unavailable.

Spatially continuous model outputs can also be used to design more efficient and cost-effective monitoring programs, especially when multiple organisations are involved. For example, adaptive sampling efforts could be targeted towards areas where prediction uncertainty is high. Citizens could be encouraged to visit areas which are easily accessible, allowing professional monitoring teams to focus on more remote areas or areas with restricted access. Models are refit iteratively as new data are submitted, which produces up-to-date uncertainty layers to inform the next stage of field sampling.

Spatially continuous and temporally dynamic predictions can also be used to improve reef-related management decisions relating to threats such as land-based pollution, coral bleaching, or fishing impacts. Understanding where the most vulnerable reefs are and how those risks change over time is the first piece of information managers need to make more informed decisions. Once they have a clear picture of current conditions, then they can start to optimise scarce monitoring and restoration resources to ensure that resources are allocated in the most effective way possible. This would allow managers to make data-enabled decisions about where and when to pull management levers that are associated with trade-offs between environmental, social, and economic benefits to stakeholders.

Online community platforms provide a rich set of tools to encourage the formation and integration of stakeholders in the Reef's future. This rich set of community tools will enable experts, tourists and business owners to contribute and share information to facilitate greater ownership of the future of the reef. Online forums, communication platforms and data sharing offers the potential for everyone with a stake in the reef to assist with monitoring its health, and to potentially profit from these contributions. Community groups will be able to utilise these data at a local scale to encourage reef protection. Businesses will be able to contribute to sustainable practices in their activities on the reef from up-to-date knowledge. The synergies created from having both experts and local people in the community will, we believe, produce new knowledge as these two groups interact more closely. Such a space will provide a secure future for the reef environment by encouraging good stewardship practices by all stakeholders based on up-to-date local and whole-of-reef scale knowledge.

Future Directions

The main goal of the Monitoring Through Many Eyes project was to develop a prototype system that demonstrated the benefits of a visually immersive and predictive approach for reef monitoring and management. As the project developed, we actively engaged with organisations whose core responsibility it is to monitor, assess, and manage the GBR (AIMS and GBRMPA). As a result, we are currently talking with partners about opportunities to operationalise the system.

The implementation of this project revealed a number of challenges induced by being at the frontier of the science. These challenges represent opportunities for future research, perhaps as part of a follow up project. Five examples of these opportunities are as follows. First, annotation of 2-D images is still novel in both the computer science and statistics fields, and very little has been investigated on annotation of 360-degree images. We endeavoured to do this in our project but we elected to defer this until we can institute the required scientific protocols in order to obtain rigorous results. A second and related opportunity is how to better estimate coral cover on a sphere. This involves sophisticated mathematical and statistical formulation which, while initiated, will require finalisation and validation past the life of this project. Third, although a novel integrated modelling framework has been established, it was challenging to fully demonstrate its potential with covariates reported at a spatial scale of 500 m^2 and averaged over 50 years. We anticipate that the model results will improve as data at finer spatial and temporal resolution become available. Fourth, modelling coral cover across the Great Barrier Reef is really difficult. This is evidenced by the many proposed models and published articles on this topic. In our case, we were modelling not only over large spatial and temporal scales, but also over multiple coral genera, which each respond differently to different disturbances. Notwithstanding the novelty of the weighted aggregation approach that we developed, the Bayesian GLMM model that we adopted can be improved. Finally, we firmly believe that citizen science can play an important, and indeed critical, part in scientific monitoring, and we have demonstrated the way in which this information can be used positively rather than dismissed arbitrarily. However, there is more to be done on learning how to improve on the way that we elicit and represent this information, and on how we continue to educate our citizens to be part of the scientific monitoring effort.

Although the prototype platform was developed for a citizen-science project in the GBR, the concept is transferable to other systems and data types. For example, a similar workflow could be implemented in catchments to monitor and model river discharge in near-real time. Image-based sensors are currently in development that estimate river flows at a fraction of the cost of traditional gauging stations. At the same time, a platform such as this would allow citizens to contribute photos of stage height. These disparate data sources could be integrated with traditional gauging-station data, and after accounting for their various levels of uncertainty, discharge could be predicted continuously throughout a catchment in near-real time; thus, providing vital information for flood prediction and advanced warning for extreme events, and water allocation, as well as modelling of sediment and nutrient loads.

Similarly, the existing platform could be modified to solve other catchment-monitoring issues where large amounts of data are needed to enhance management strategies. Information can be automatically extracted from high-resolution remote-sensing data to help monitor illegal land-clearing activities or changes to ground cover on public and private lands. Citizens could be encouraged to submit ground-based images, which are subsequently used to validate classification and change-detection algorithms. This information has obvious value in terms of compliance monitoring, but it could also be used to promote, monitor, or certify best-management practices on private lands, leading to positive benefits to private land holders. These benefits could be direct, such as gaining or maintaining market access through environmental certifications. However, indirect benefits may also include an improved environmental reputation, which builds trust with the public, and makes private land owners more resilient to public-license-to-operate issues, such as land-based pollution to the GBR.

Our platform provides the essential infrastructure to enable large-scale communities of divers and reef experts to contribute local knowledge, which is subsequently used to improve model and management outcomes. However, this can be extended much further by implementing online community and gamification tools. Previous work highlighted in the "Snapshot Serengeti" community shows the potential of future work in this area. For example, gamification can be used in such communities to enhance the skill levels of contributors utilising approaches from video game systems. Research showing the effectiveness of such gamification (Hamari et al. 2014) can be exploited to provide greater engagement and thus better quality information, which creates ongoing positive effects by better modelling and feedback. This online gamified community can then become a real-time test bed used to evaluate the potential use of improved models in increasing public awareness and education, scientific research, commercial opportunities and other activities related to the GBR.

Our use of VR technology also creates new and innovative approaches to visualisation. Online expert communities can be created in advanced immersive 3D VR environments, which have been shown to enhance collaboration by enabling remote teams to work effectively together (Gupta et al. 2016). International experts can collaborate remotely, viewing 3D data, which can be an effective way to assist in environmental modelling and sustainable community practices. There are also opportunities to significantly extend the visualisation capabilities of such a system. Scenarios represented using model predictions generated by model predictions or real-life imagery could be viewed in 2D, or in immersive 360-degree or 3D environments to help users understand the spatio-temporal drivers of events such as floods in urban areas, droughts in agricultural landscapes, or flooding effects on the Great Barrier Reef. Broader community stakeholders may also benefit from narrative style 3D visualisation playing out scenarios in a direct story-based manner that will help communicate complex environmental processes, model results, and uncertainty. Such narrative visualisations support insight by providing a story that guides the users through the key elements of the visualisation. However, steps must be taken to ensure that the information conveyed in the visualisation is not misinterpreted by users, leading to unexpected and erroneous outcomes.

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- Australian Institute of Marine Science (http://aims.gov.au/)
- Reef Check Australia (www.reefcheckaustralia.org/)
- University of Queensland (UQ) Remote Sensing Research Centre (https://www.gpem.uq.edu.au/rsrc)
- UQ Global Change Institute (http://www.gci.uq.edu.au/)
- XL Catlin Global Reef Record (http://globalreefrecord.org/home_scientific)

References

Gelman A, Carlin JB, Stern HS, Dunson DB, Vehtari A and Rubin DB. 2013. Bayesian data analysis, third edition. CRC Press.

González-Rivero M, Beijbom O, Rodriguez-Ramirez A, Holtrop T, González-Marrero Y, Ganase A, Roelfsema C, Phinn S and Hoegh-Guldberg O. 2016. Scaling up ecological measurements of coral reefs using semi-automated field image collection and analysis. Remote Sensing, 8:1.

Gupta K, Lee A and Billinghurst M. 2016. Do you see what I see? The effect of gaze tracking on task space remote collaboration. IEEE Transactions on Visualization and Computer Grahics, 22(11): 2413-2422.

GBRMPA (2014). Great Barrier Reef Marine Park Authority. Available at: http://www.gbrmpa.gov.au/geoportal/.

Hamari J, Koivisto J and Sarsa H. 2014. Does gamification work? A literature review of empirical studies on gamification. In: System Sciences (HICSS), 2014 47th Hawaii International Conference on System Sciences. 6-9 Jan, 2014, Waikoloa, HI, USA. Pages 1530-1605.

Harman J, Brown R and Johnson DM. 2016. Augmenting process elicitation with visual priming: an empirical exploration of user behaviour and modelling outcomes. Information Systems, *in press*.

Johnston C, Smith A and Dyke J. 2013. Defining the aesthetic values of the Great Barrier Reef: Report 1 Methodology. Townsville: Great Barrier Reef Marine Park Authority.

Lucas PHC, Webb T, Valentine PS and Marsh H. 1997. The outstanding universal value of the Great Barrier Reef World Heritage Area, Townsville: Great Barrier Reef Marine Park Authority.

Mumby PJ and Steneck RS. 2008. Coral reef management and conservation in light of rapidly evolving ecological paradigms, Trends in Ecology and Evolution, 23:555–563.

Plummer M. 2016. rjags: Bayesian Graphical Models using MCMC. R package version 4-6. https://CRAN.R-project.org/package=rjags

Pocock C. 2002. Sense Matters: aesthetic values of the Great Barrier Reef. International Journal of Heritage Studies, 8:365-381

Wood SN. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. Journal of the Royal Statistical Society (B) 73(1):3-36

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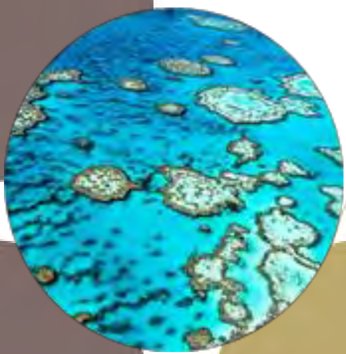


Monitoring Through Many Eyes: Spatially enabling people to protect the Great Barrier Reef

Stage 2 – Report 2/4

Installation Guide

a university for the real world®

22th December 2016

About us

The Monitoring Through Many Eyes project is a multidisciplinary research effort designed to enhance the monitoring of the Great Barrier Reef. The project aims to create a virtual reef by geotagging underwater photos and videos contributed through citizen science. These will be used to create immersive environments that will help to improve estimates and predictions of the health of the Reef. Our mission is to deliver new know-how in visualisation and spatial statistical modelling, new spatial products, and a new avenue for the public to engage in monitoring the reef.

Table of Content

Introduction

There are 2 distinct software components to the Monitoring Through Many Eyes website and supporting modelling framework.

- Windows Server 2012 R2 - Virtual Machine (VM)
- Microsoft SQL Server 2012

The VM will be delivered as a packaged image, although where applicable, documentation is provided below to highlight custom installation steps performed.

The core component of the application resides in a traditional Microsoft web application based architecture, using Internet Information Services (IIS) and ASP.Net to communicate with SQL Server database, preferably hosted on a database cluster or separate machine.

A separate structure and content creation script will be supplied, to allow the creation of a SQL database with the minimum required tables and data to run the application.

This document will detail configuration steps, and software installation guidelines used in the creation of the web server, database instance and the modelling framework implemented within the server architecture.

1. Recommended Hardware Requirements

The following hardware requirements are a standard, low overhead web server specification used by QUT. The application has been tested thoroughly in this environment, and is considered the minimum recommended hardware requirements.

Operating System	Windows Server 2012 R2 Standard
Processor	Intel® Xeon® CPU E5-2680 @ 2.70 GHz
Installed RAM	4.00Gb
System Type	64-bit Operating System, x64-based processor

2. Windows Server 2012, R2 Virtual Machine (VM)

The Windows server has 3 roles within the application architecture.

1. Serve the ASP.Net website with IIS which allows data upload, users to perform elicitations and view the modelling output and source photographic images.
2. Provide REST endpoints for data transfer services between the website, VR application and modelling framework.
3. Process the statistical modelling, via R scripting, through a scheduled task

2.1 Internet Information Services (IIS) Requirements

Best practice guides have been followed in the configuration of the IIS instance, and the server has been through several rounds of vulnerability scanning through QUT's network security software suite. Changes were also made within the ASP.Net website code base, to meet the QUT security requirements.

2.1.1 SSL Certificate

The supplied VM is setup with the use of an SSL certificate, currently for www.virtualreef.org.au, but this can be altered to suit any domain, or removed for internal protected networks.

The SSL certificate was configured for a variety of best practice security measures, enforcing the use of HTTPS data transfer through the website. These include the protection of users' credentials when registering and authenticating with the application and verifying the identity of the website sending and receiving the users' data.

2.1.2 ASP.Net Support

The web application was written using the ASP.Net version 4.5 codebase. Support should be installed for this version, and the appropriate Application Pool given the same version support.

The authentication support for the application pool user should be tailored to your network environment.

If ASP.Net 4.5 is added after the IIS installation, be sure to register the DLL's using:

"%windir%\Microsoft.NET\Framework\ v4.0.30319\aspnet_regiis.exe"

"regsvr32 %windir%\Microsoft.NET\Framework\v4.030319\aspnet_isapi.dll"

2.1.3 Uploads Directory

The website received photographic submissions through an upload form on the website. This requires Write access to the ~/uploads directory for the relevant IIS_USR account on which the connection is being made.

The uploads directory can be alternatively configured to be hosted in an alternate drive location, and mapped as a *virtual directory* through IIS.

Upon the upload of a file through the website, a unique GUID string is generated to rename the file, ensuring no clashing of file names from different users.

Additionally, thumbnails are created and stored in the appropriate sub folder, the size determined from the web.config settings. The thumbnails are used in the exploration interface on the website.

2.1.4 Web Config settings

There are several areas of the web.config file which manage global settings for the website. It is assumed the user of this guide has an understanding of the web.config settings that are common to typical ASP.Net application development.

2.1.4.1 Application Settings

The location of the upload directory is detailed in the first application setting. The remaining settings determine the size of the thumbnails generated during the upload process.

```
<appSettings>
  <add key="ImageStoreBasePath" value="https://www.virtualreef.org.au/uploads/" />
  <add key="smallThumbnailSizeWidth" value="54" />
  <add key="smallThumbnailSizeHeight" value="54" />
  <add key="largeThumbnailSizeWidth" value="400" />
  <add key="largeThumbnailSizeHeight" value="150" />
</appSettings>
```

It should be noted that updating the thumbnail size settings will not retroactively resize the thumbnails that have been previously generated.

2.1.4.2 Mime Types

It is a requirement of both the Cesium 3D mapping framework, and the REST service endpoints that support for the JSON mime-type is supported. This can only be configured in either the web.config settings as detailed below, or in IIS as a permanent mime type mapping

```
<staticContent>
  <remove fileExtension=".json" />
  <mimeMap fileExtension=".json" mimeType="application/json" />
</staticContent>
```

2.1.4.3 Connection Strings

The authentication to the SQL database is detailed using connection string stored in plain text within the configuration file. For the purposes of this document, it has been redacted from the sample, replaced with SERVERNAME, DATBASENAME, USERNAME and USERPASSWORD

```
<connectionStrings>
  <add name="IFE_GBREEF_DEVEntities"
connectionString="metadata=res://*/Model1.csdl|res://*/Model1.ssdl|res://*/Model1.msl;
provider=System.Data.SqlClient;provider connection string=&quot;data
source=SERVERNAME;initial catalog=DATABASENAME;persist security info=True;user
id=USERNAME;password=USERPASSWORD;MultipleActiveResultSets=True;App=EntityFramework&qu
ot;" providerName="System.Data.EntityClient" />
</connectionStrings>
```

2.2 Modelling Framework

The modelling framework is a collection of R Scripts and associated data files and folders, to derive the coral coverage predictions and prediction error maps, displayed in the web based 3D mapping framework.

The current iteration takes approximately 10 minutes to run through to completion on a standard modern Windows Server virtual instance. Variations to this speed will be dependent on the hardware allocations to the hosted instance.

2.2.1 Modelling Software R Scripting and GDAL

The server will require internet access for this part of the installation. It should be noted that the R Scripting proxy support is troublesome when using a restricted proxy. In this case, the library of installed R components can be copied from another machine with internet access, that has followed the same steps.

The installation of R scripting for Windows and the associated packages should be performed through the following steps:

1. R Scripting version 3.3.2 from which can be downloaded and installed from https://cran.r-project.org/bin/windows/base/R-3.3.2-win.exe

   The R application should be installed as Administrator, in the default location for the installation in Windows 64 bit OS

2. Once, installed, open the application and paste in the following command and hit Enter.

   install.packages(c("tidyverse", "raster", "maptools", "sp", "rgdal", "magrittr", "rgeos", "devtools", "jsonlite", "knitr", "lubridate", "rjson", "rgeos", "purrr", "gdalUtils", "mgcv"))

   A prompt will ask you to select the appropriate CRAN mirror, we recommend an Australian based mirror such as Melbourne or Canberra. Click OK to complete the installation of these packages.

3. Download and install GDAL

   http://download.osgeo.org/osgeo4w/osgeo4w-setup-x86_64.exe

   Select advanced install; click through until you see select packages screen.

   Go to the Libs section and select both **gdal** and **gdal-python 2.1.2**

   Ensure that these 2 packages are the only ones selected for installation before continuing.

2.2.2 Modelling Scripts RScripts and data files

The framework files, which perform the statistical analyse and generate visualisations for the predictions, must be located in a directory outside the access scope of the web application, to ensure robust security. The file interaction is to push from this modelling directory into the website folder which serves the mapping tiles.

2.2.2.1 Folder structure

Display_tiles	Prediction raster files, consumed by gdal2tiles
Inputs	The colour mapping settings for the tile outputs
Outputs	The prediction raster images, in a subfolder for each year
Rasters	The input covariate raster files

In the final stage of the tile generation, the complex folder structure and a large number of files are copied to the website tile serving directory, located at **~/models/output_tiles,** where ~/ is the root directory of the website.

The folder structure represents a WMS tiling service endpoint for the Cesium mapping framework to connect to and display. A subfolder for each layer on the map is created from the modelling scripts. A further child folder is created for each zoom level supported, as specified in the RScript.

2.2.2.2 Batch File Scheduled Task

The parent RScript, to start the model generation process, is called from a batch file called **runreefmodel.bat** containing a path the R application and the parent RScript name, contained within the same directory

"c:\Program Files\R\R-3.3.2\bin\rscript.exe" ReefModel.r

This is set to run through the creation of a Windows Scheduled Task, set to run once per week currently. The administrator of the server can set this to whichever frequency is required, depending on the rate of acquisition of new data. To ensure that the R script has permission to overwrite the generated predictions and their standard errors, stored as raster images and tiles, the batch script must be set to run as an Adminsitrator.

Future iterations of the application could consider launching this batch file from a SQL Trigger, based on the number of new records generated through the elicitation process.

3. SQL Server Database Instance

The data behind the website, modelling framework and VR application is all contained within a Microsoft SQL Server database.

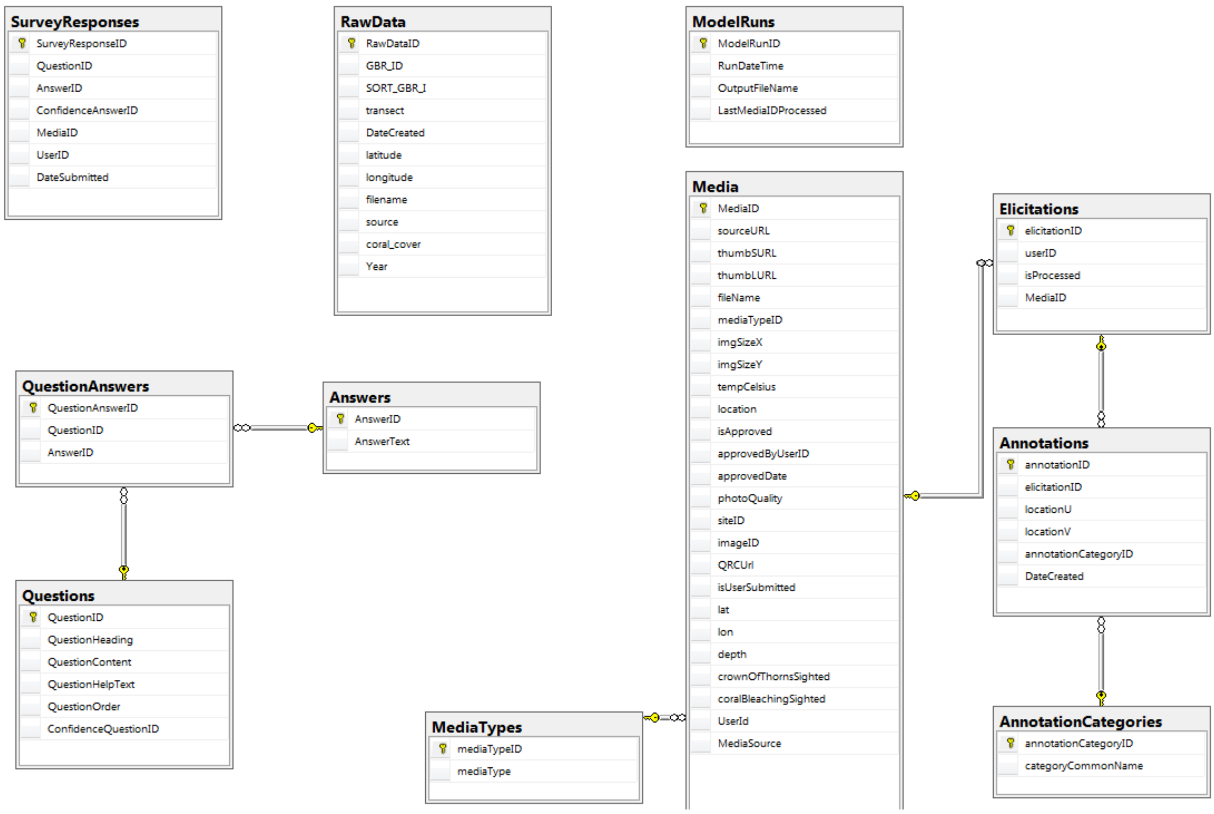
A Backup of the database, with non-essential data removed, will be supplied as part of the software deliverable package. This will be supplied as a large SQL script, also containing data inserts after the table creation scripts.

The database is currently hosted on Microsoft SQL Server Enterprise Edition (64-bit), on the internal QUT server **SQLQUT01-DEV**. The database is named "**IFE_GBREEF_DEV**"

It contains the traditional Microsoft Identity tables for Membership provision, these tables are all prefixed with Asp.Net and are not featured in the database architecture diagram below, as they are independent of the customised data structure created for this application. The relationship to the membership provider and the customised table is maintained through the UserID field, unique to each user account.

Access to the database is through a SQL Server identity, passed through the web.config file in the ASP.Net application, detailed in the Connection Strings section previously in this document. All data structure is maintained through the Entity Framework instance on this connection, created and served within the website framework. This authentication method can be modified to suit the target hosting environment, by editing the connection strings.

The database table design and relationships can be seen in the following diagram



4. GIT Repository

Supplied as part of the deliverable is a copy of the projects GIT Repository. The following documentation provides a high-level overview of the folder structure and contents.

4.1 Framework/Windows

These are the folders for the modelling component of the application. These are currently set up to be deployed to D:\REEFMODEL folder, copied from the Windows folder in the repository. The framework requires the installation of RScript and GDAL as detailed in earlier sections of this guide.

There are several path locations contained within the framework files which should be checked and modified to suit the new deployment environment:

ReefModel.R
Update this file to point to the location of the framework files, defaulting to D:\REEFMODEL

modelling_mgcv_gendata.R
The purpose of this file is to pull down the raw data from the REST endpoint where it is stored, and perform the aggregation for each source for each year and within the cells of a reference raster. This file also calls modelling_support.R to load in support functions and modelling_ReefCheck.R to obtain the citizen science data and appends it to the monitoring data after aggregating. Covariates are extracted from the covariate rasters for each spatial cell and year and joined to the aggregated data frame.

Update the endpoint locations in this file to point to the domain name where the REST endpoints have been hosted. Defaults to https://www.virtualreef.org.au/api. It should be noted there are two entries in this file to be updated with the correct endpoint locations.

This file contains a flag that indicates whether already aggregated data are available.

modelling_support.R

This file contains specifications of support functions required to do the data aggregation for modelling_mgcv_gendata.R.

modelling_ReefCheck.R
This file obtains citizen science data from REST endpoints that contain annotations of citizen science images from Reef Check and professional survey images from the XL Catlin Seaview Survey. The accuracy of each user is calculated by comparing the elicitation of 20 reference images from XL Catlin to the elicitation of those same images by an expert. Weights are derived from image properties and accuracy rates to calculate weighted means of the coral cover estimates derived from users performing elicitations on the Reef Check images.

Update the endpoint locations in this file to point to the domain name where the REST endpoints have been hosted. Defaults to https://www.virtualreef.org.au/api. It should be noted there are two entries in this file to be updated with the correct endpoint locations.

modelling_mgcv_purrr.R

The purpose of this file is to fit a Beta GLMM to the aggregated data and provide predictions. This file contains a flag for whether or not the data should be subsetted according to Management Zone and the shelf location. Outputs are the same format regardless of whether the data are subsetted and fitted individually or all at once.

modelling_mgcv_output.R

The purpose of this file is to take the model predictions and their standard errors and write a TIF raster image for each year for each of these. These are stored in the \outputs\ folder.

gdal_tiling.R

This file provides functions to colormap the output rasters as PNG files, and to tile the rasters for web display.

The path for the GDAL installation is defined in this file. Be sure that the entry for C:/OSGeo4W64/OSGeo4W.bat is pointing to the correct location. This is the default installation location for the application installed in the latter part of the Framework installation guide earlier in this document.

actually_tiling.R

Calls the functions specified in gdal_tiling.R to generate prediction tiles for the chosen years (currently 2004, 2012 and 2016).

Contains several important path locations. This part of the modelling script creates the tiled layers for display on the website, hence paths need to point to the location of the IIS instance.

Replace c:/inetpub/wwwroot/Reef_Web with the root of the IIS instance, in several locations. Replace setwd("D:/REEFMODEL") with location of the modelling files folder.

4.2 SQL_Server

Contains a scripted file for the creation of the tables and data for the baseline database content. This SQL script should be run in a newly created database. Security settings will be dependent on the hosted environment, and should be updated in the web.config file to suit.

All proprietary monitoring data have been removed prior to delivery, including elicitation data gathered during the development phase of the project. Images which have been licensed to QUT for redistribution have been retained in the database for delivery. A document containing the sources of the rasters and shapefile data, and images, has been provided with the delivered reports, detailing the licensing of the data and who to contact for licensing.

4.3 Virtual Reality (VR)

The VR folder is a Unity project folder that can be opened directly in the Unity 3D (https://unity3d.com/) editor. The project requires Unity version 5.5.0f3 or later. Currently the application supports only Samsung Gear VR (Oculus) platform running on Android devices.

The VR application is built for the Gear VR platform using the Unity Android build target. To setup the environment for deploying to Gear VR, both Unity and the mobile phone will need to be configured for Android development. The Android SDK will need to be installed on the same PC as the Unity install, and USB debugging needs to be enabled on the Android phone.

Each device that requires application deployment from Unity, also needs to have an Oculus signature file generated on the Oculus website, and copied into a location within the Unity project, before deployment. The signature file generator requires the Android phone device ID which can be found using the "**adb**" tool provided with the Android SDK. To connect your Android phone to the Windows PC and deploy applications, you will need to install the appropriate USB drivers. The Android SDK, ADB tool, and USB drivers are available to install using the Android SDK manager.

Please follow the links and instructions below to setup the required components.

For full instructions to download the Android SDK and setup Unity for Android development, see here https://docs.unity3d.com/Manual/android-sdksetup.html

To install the SDK manager, you can install as part of the Android Studio Bundle which includes the SDK and tools, or it is also possible to download the SDK by itself. You can find the Android installations here https://developer.android.com/studio/index.html

To use the ADB tool to retrieve your Android device ID, you must enable a feature called Developer Options and USB debugging. Open your phone's Settings menu, and select "About Device". Scroll all the way down and tap the "Build Number" item seven times. You should get a message saying you are now a developer. A "Developer Options" item should now be available at the bottom of the Settings menu. You need to enable "USB debugging" option in the Developer Options.

Plug in the Android device via USB, and make sure the phone is unlocked (a message may appear on the phone screen requesting access to USB debugging, select OK to agree to this). Then you can use the ADB tool to access the device ID. Open a Command Prompt on the PC and type:

adb devices

You should see output similar to this:

List of devices attached

04157df41d2d8806 device

This number is your device ID (example 04157df41d2d8806). Copy this number and use the Oculus signature file generator tool to generate you signature for this device, for use in Unity. The signature generator tool can be found here https://developer3.oculus.com/documentation/mobilesdk/latest/concepts/mobile-submission-sig-file/

You will need to be registered with a free Oculus account to access the generator. Paste the device ID into the form field and generate and download the signature file.

Place a copy of this file in the Unity project folder in "**Project/Assets/Plugins/Android/assets/**". Note that you may include multiple signature files in a single application in order to support multiple devices within your organization. With the phone still connected, you should now be able to build the Unity application to the device.

4.4 Website

Contains the ASP.Net 4.5 website, built in Visual Studio Community 2015. Included in the root folder is the solution file for the project. This should be built and deployed to an IIS hosting instance, noting there are both production and development web.config settings included.

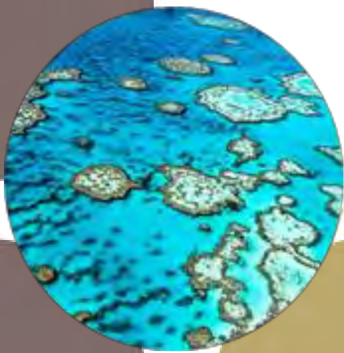
5. Acknowledgements

We would like to acknowledge the Cooperative Research Centre for Spatial Information and the Queensland Department of Natural Resources and Mines for providing funding for this research.

The team also collaborated with citizen science and research organisations to conduct our experiments and receive contributions of data and images. We would like to give a big thanks to our collaborators/contributors – this project would not be possible without them.

- Australian Institute of Marine Science (http://aims.gov.au/)
- Reef Check Australia (www.reefcheckaustralia.org/)
- University of Queensland (UQ) Remote Sensing Research Centre (https://www.gpem.uq.edu.au/rsrc)
- UQ Global Change Institute (http://www.gci.uq.edu.au/)
- XL Catlin Global Reef Record (http://globalreefrecord.org/home_scientific)

Monitoring Through Many Eyes: Spatially enabling people to protect the Great Barrier Reef



Stage 2 – Report 3/4

User Guide

a university for the real world®

22th December 2016

About us

The Monitoring Through Many Eyes project is a multidisciplinary research effort designed to enhance the monitoring of the Great Barrier Reef. The project aims to create a virtual reef by geotagging underwater photos and videos contributed through citizen science. These will be used to create immersive environments that will help to improve estimates and predictions of the health of the Reef. Our mission is to deliver new know-how in visualisation and spatial statistical modelling, new spatial products, and a new avenue for the public to engage in monitoring the reef.

Table of Content

Introduction

This document is a non-technical instruction on using the software, directed at reef experts and non-experts alike. The intention is to show typical workflows for uploading of images, exploration of datasets, and performing elicitations using the VR interfaces.

System Overview

The overall structure of the systems implements the infrastructure vision via four major components: Web Interface, Virtual Reality (VR) Experience, Modelling, and Workflow Framework (Figure 1). In this user manual, we will focus on the web and VR interfaces and their user accessible functionality. Backend functionality is described in the main report and the technical installation document in the source code repository.

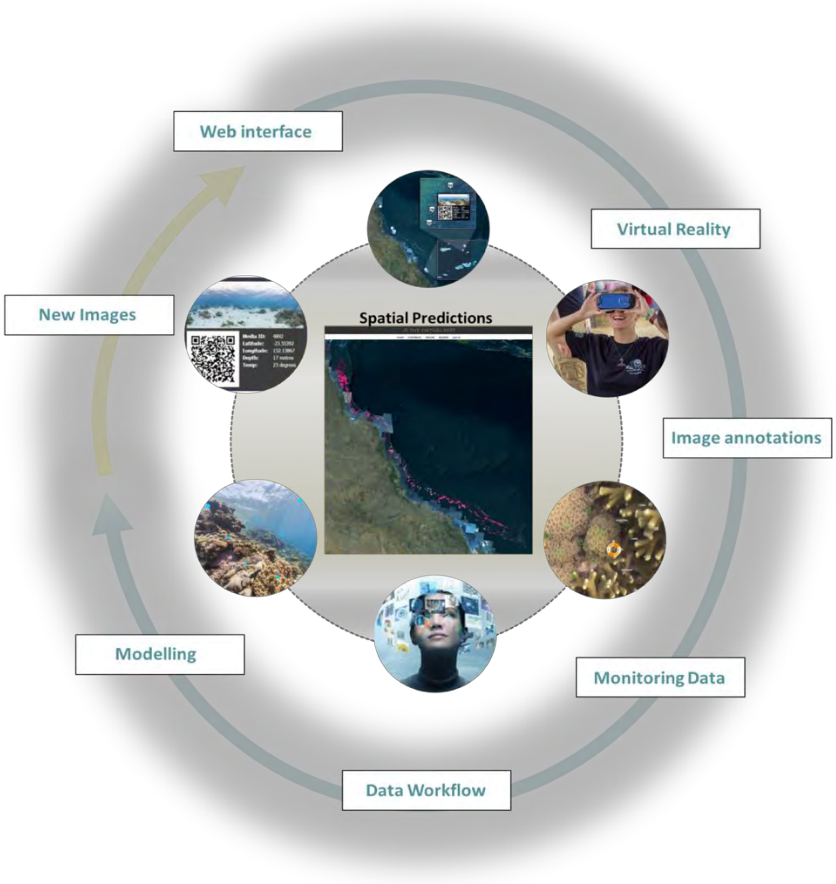


Figure 1. Overview of the Monitoring Through Many Eyes project components.

1. Using the Website

1.1 Website Overview

This section describes in detail the usage of the web interface within our prototype.

The website component of the application has several key roles in the delivery of the project functionality. It allows a user to:

- Learn about the project, its core objectives and the role citizen scientists or subject matter experts can play in the contribution of imagery and elicitation of analytical data.
- Upload and contribute both 2D and 360-degree imagery to the project for users to annotate and locate within the project bounds of the GBR.
- Explore the imagery and modelling outputs in a web-based map engine.
- Register a user account and login, to allow a personalised contribution experience.

1.2 Introductory Page

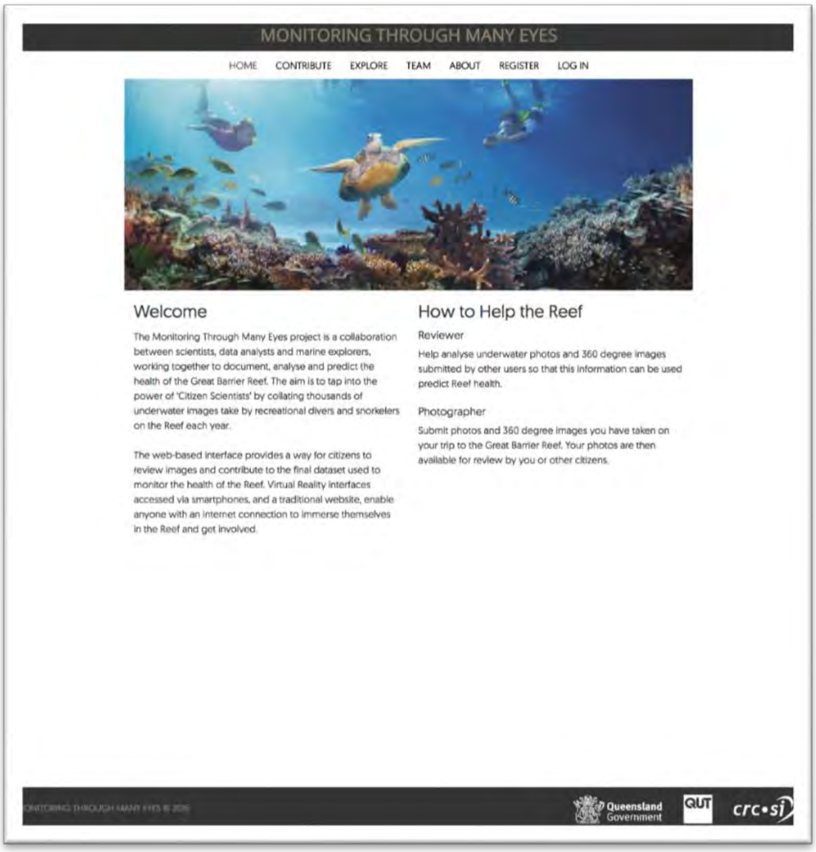


Figure 2. Home page of website with explanatory text and menu.

A main menu is provided on the front page to traverse to the various functionalities of the prototype (Figure *3*).

Figure 3. Enlargement of banner and menu displayed on the main website page.

Broadly, the menu structure reflects the main functionality of the website:

1. *Home*, *Team* and *About* menu options - non-interactive information pages;
2. *Contribute* - image upload facilities for experts and laity;
3. *Explore* - map-based image and spatial model interface;
4. *Register and Log In* - provides upload and elicitation activity information for the user.

We now explain these in turn.

1.3 Home, Team and About menu options

There are several non-interactive content pages within the website, providing information on the following subjects:

- **Home Page** – Project overview and introduction, project objectives and graphical banner as the entry point to the website (Figure *2*);
- **Team Page** – A detailed list of the project team members and their various roles within the project;
- **About Page** – a more detailed exploration into the project technologies, workflow and framework structure.

Please refer to these pages on the website for detailed information as to their content.

1.4 Contribute

An important aspect of the project is the contribution of both 2D and 360-degree imagery for the website to contribute to spatial statistical models. The imagery is then used in elicitation functions to provide extra knowledge for the spatial statistical models. This imagery can come from both casual divers and expert professional divers.

A user must be authenticated (via creating a user account) to use the contribution form, ensuring a higher quality of data and the allocation of weightings to a user's ability to provide images of a certain quality. Contributions made by a user can be seen in a simple list format on their "My Profile" page once completed.

To begin adding their photos, a user selects the *Contribute* menu item. Using a traditional upload selection or drag and drop methodology for a JPG file. The file is selected from the local computer or device and uploaded, allowing any available geo-located EXIF metadata (location coordinates etc.) to be extracted (Figure *4* and Figure *5*).

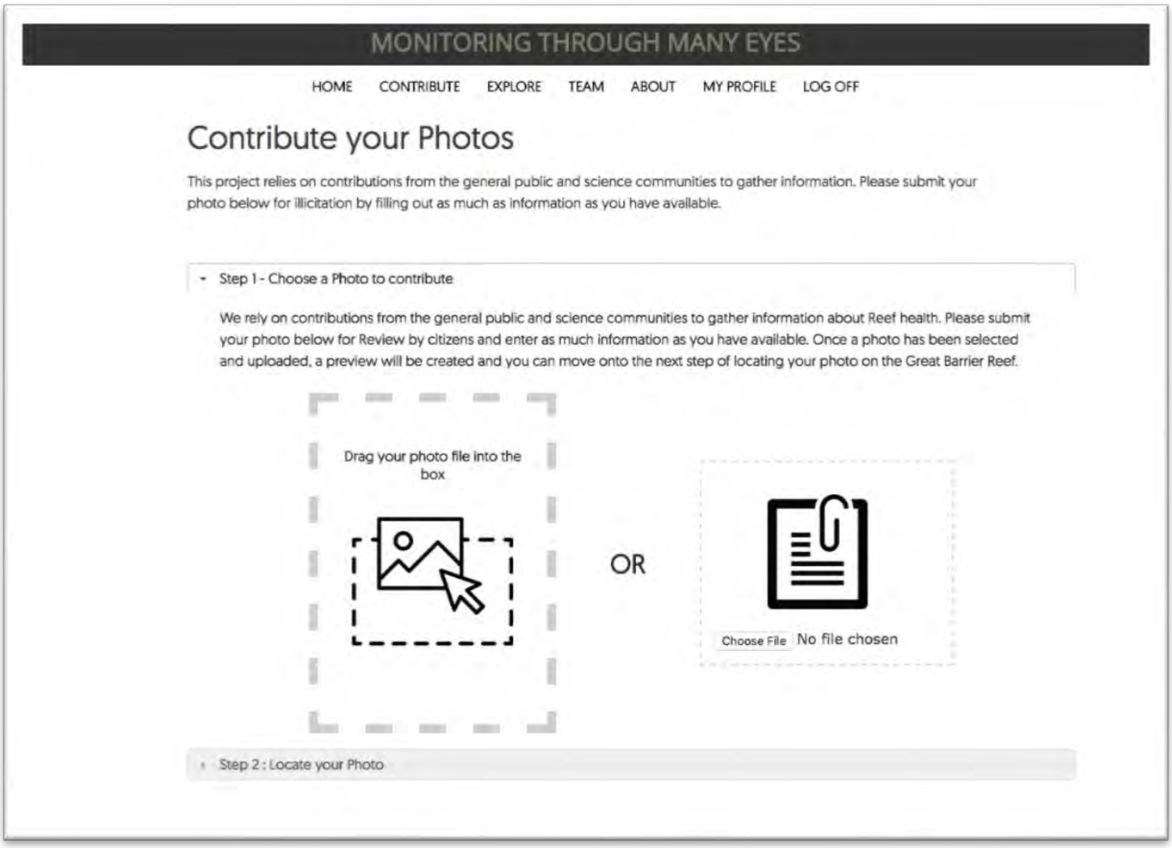


Figure 4. User interface for uploading images. Left section utilises drop and drag, while to the right the user can use a dialog box to upload images.

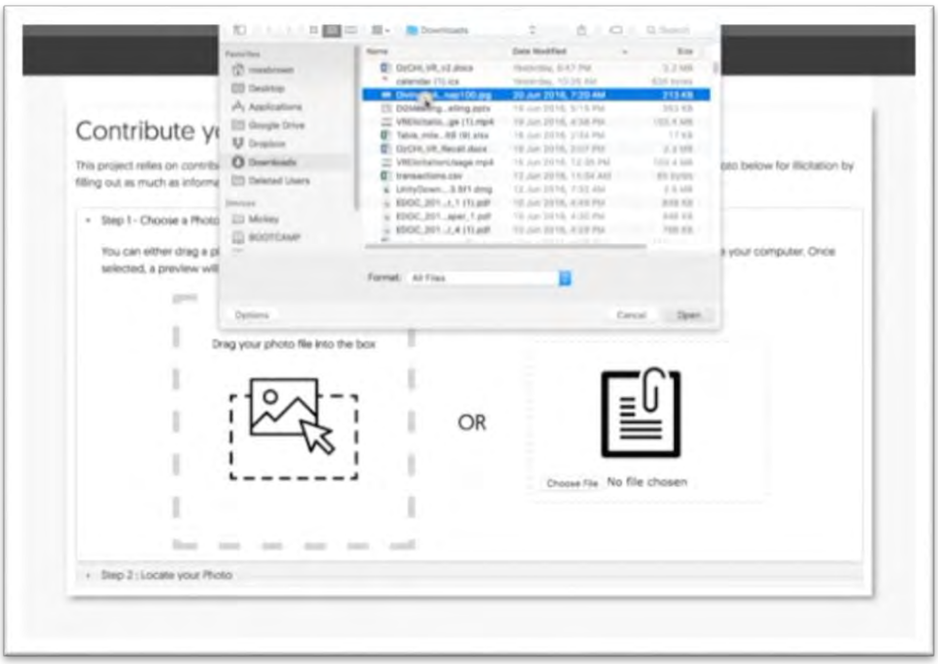


Figure 5. Dialog approach to uploading an image.

If no geo-location metadata exists in the image file to automatically place the image, then the user is requested to identify the location of the photo on a map using a drag and drop pin (Figure *6*). Users can grab the drop-pin and move it to the correct location before pressing the *Submit Your Image* button

In addition, once located, data relating to the dive spot is captured from the user, including:

- Is the photo a 360-degree image, or a traditional 2D photo?
- Did the user identify Crown of Thorns starfish within the photo?
- Did the user identify any signs of Coral Bleaching within the photo?
- At what depth was the photo taken, in metres?
- If available, what temperature in Celsius was the water at this location?

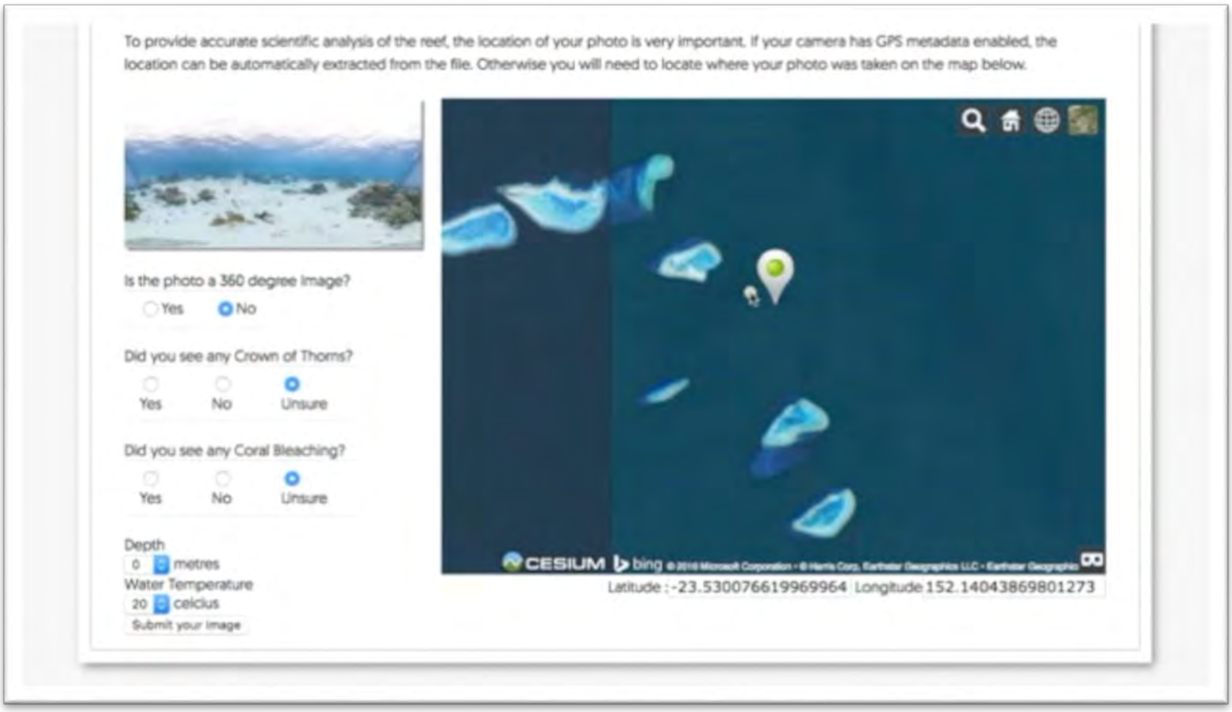


Figure 6. Using pin drop interface to geo-locate non-EXIF imagery, along with dive spot data questions on the left.

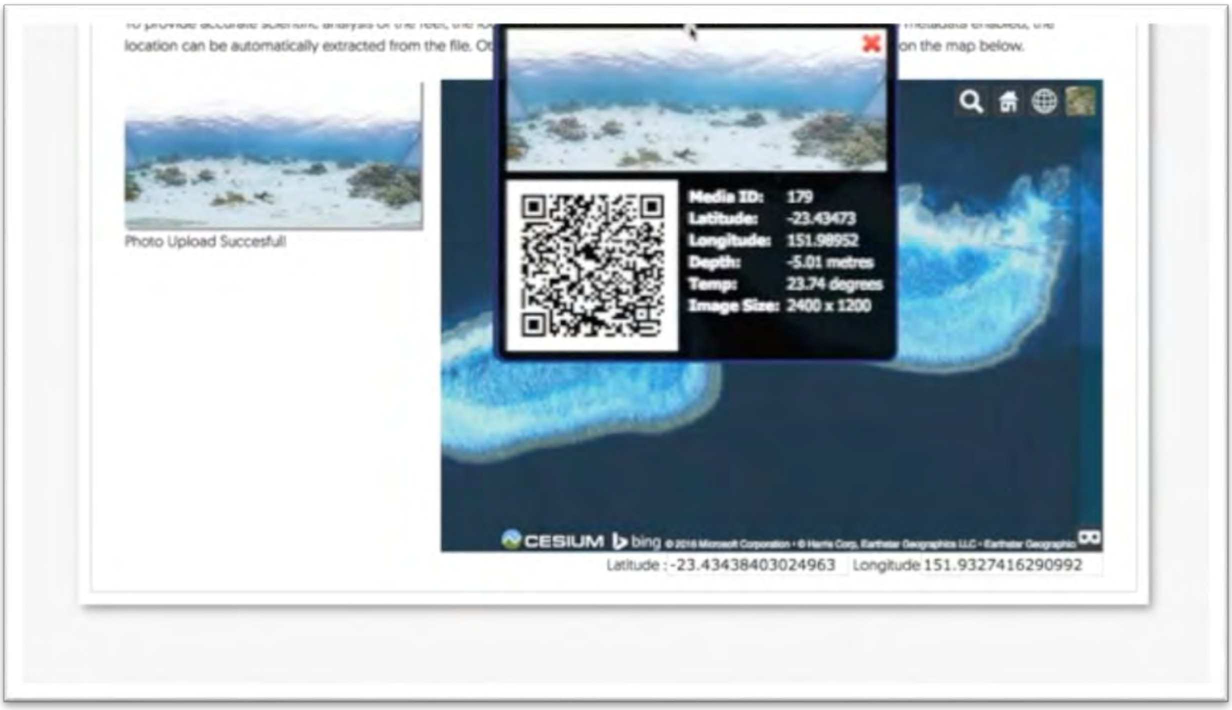


Figure 7. Successfully uploaded image showing its newly generated QR code.

Upon completion of the upload form, the file and metadata are submitted for processing into the framework, including the renaming of the file to a unique name, resizing the image for display on the website and in the VR environment, and the generation of thumbnails for use in the map and popup interfaces. At this point, a unique MediaID is generated for each image submitted, which identifies the imagery and location throughout the interface, data processing and modelling. This is shown as a QR code on the dialog to be used (Figure *7*) with the VR application in Chapter 2.

1.5 Explore

The Explore page exposes the image and model databases within the application. It can be used to view the predictive modelling output across the entire reef, navigate images in the environment or provide expert information via elicitation interfaces. To access the different datasets, the user selects from either the photography or modelling layers in the floating menu over the map (Figure *8*). This is the main jumping off point for any investigation of the map-based data.

Figure 8. Multiple layers are available within the Cesium map, which provides an overview of the Great Barrier Reef, Queensland.

We now cover the tasks that can be performed within the exploration interface, viz., visualising image, prediction and error layers.

1.5.1 Image layers

Image layers have their own grouping at the top of the menu in the top left hand section of the Explore interface (Figure *8*). Selecting them will populate the map with images (Figure *9*). Groups of images close together at the zoom level of the map view will be shown as coloured groups, with the number of images printed on the icon. Relative to the size of the image, if the spacing of the images in sparse enough at the zoom level (specified by the middle wheel of the mouse) single images will appear (Figure *11* and Figure *12*).

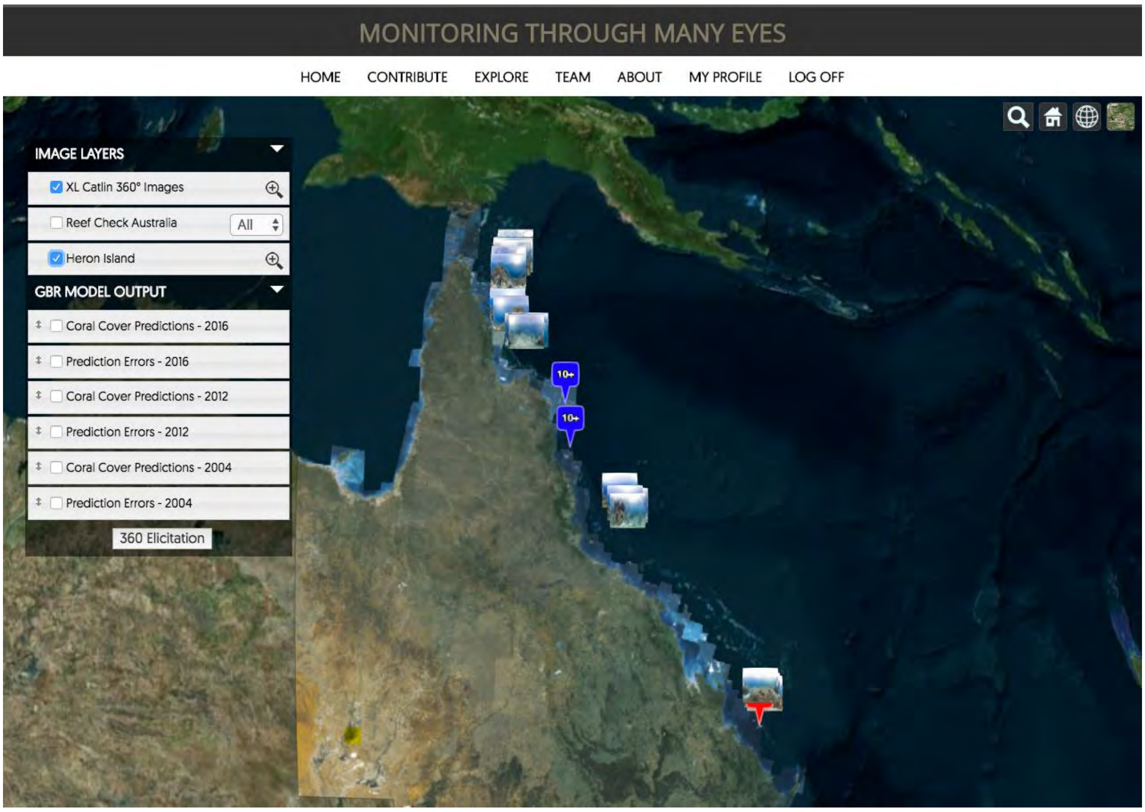


Figure 9. Map populated with images selected in left menu; in this case Catlin and Heron Island data set images.

Imagery layers have the capability to be turned on or off, zoomed into the viewport, and for larger datasets, provide a dropdown box allows the selection of a subset of the data for that layer (Figure *10*).

Figure 10. Drop down menu for Heron Island data set to select a smaller subset of images for easier traversal and manipulation on the map.

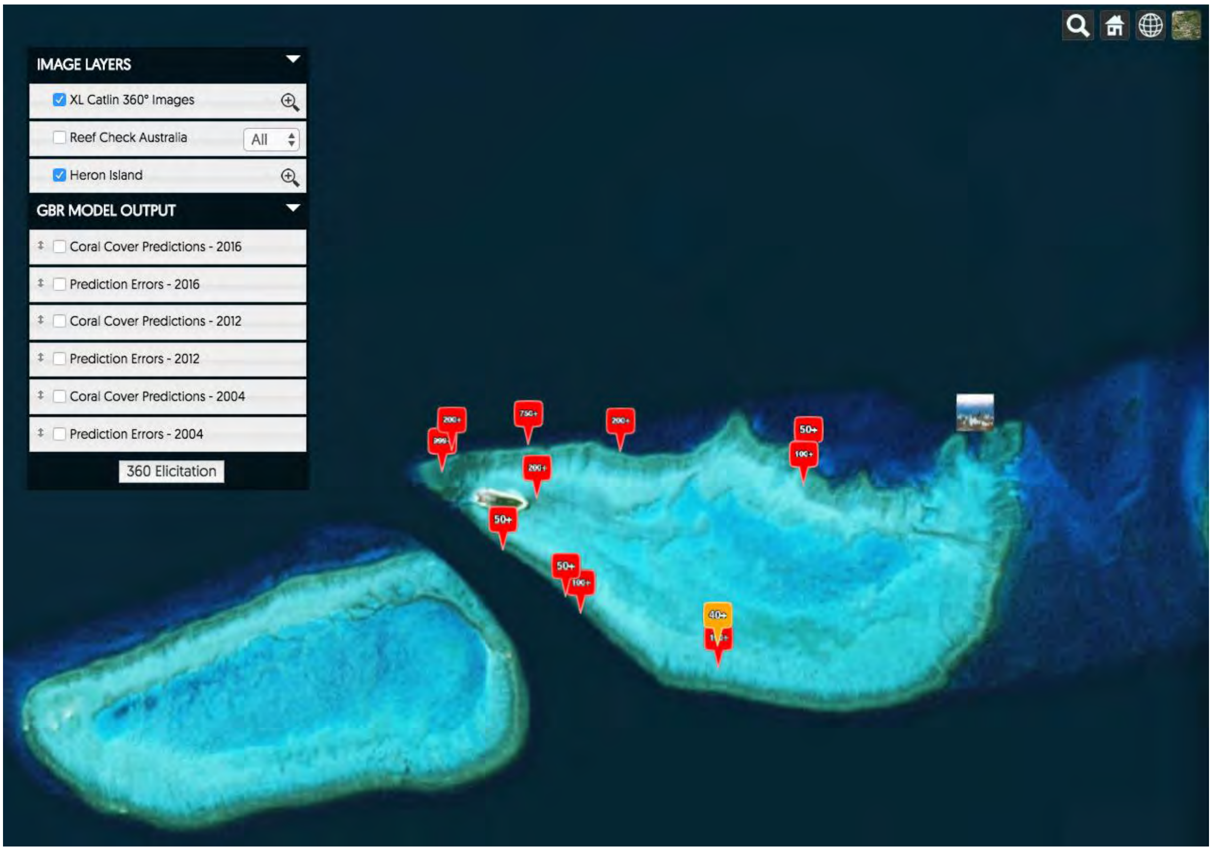


Figure 11. Image of map zoomed with mouse wheel to Heron Island showing image groups and separate images.

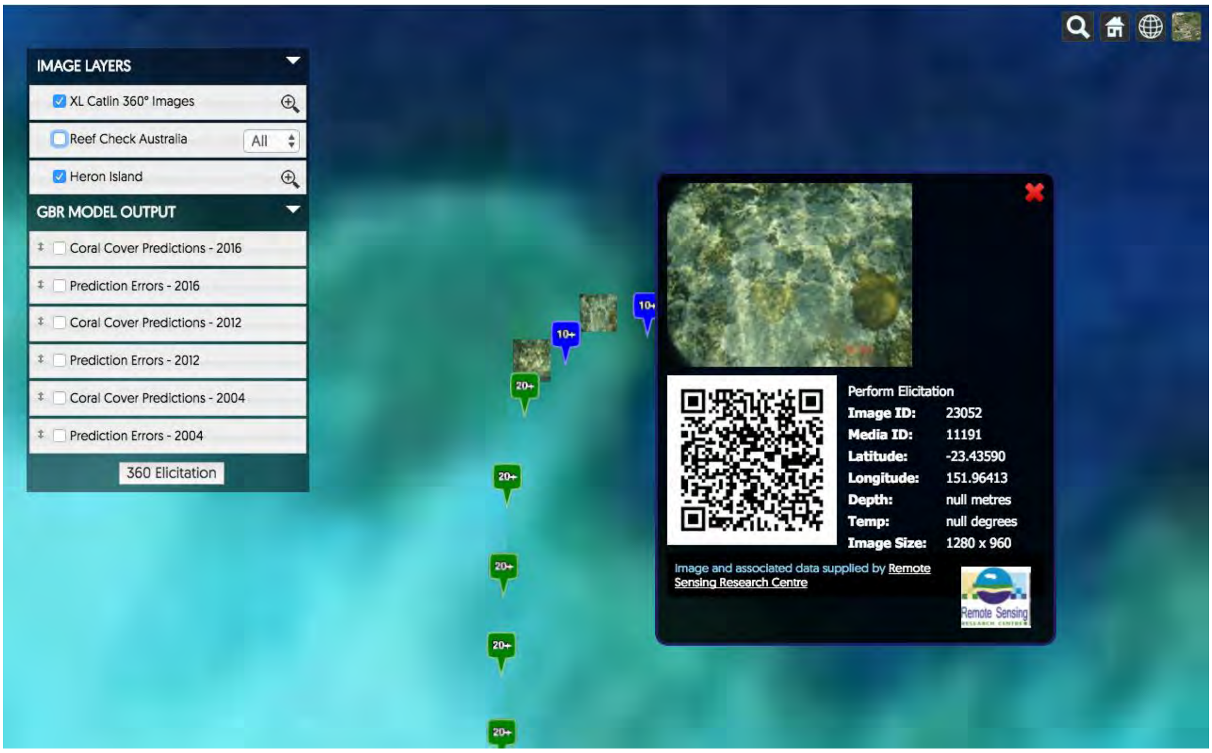


Figure 12. Image layer with Heron Island dataset active and one **2D image** selected and highlighted with its QR code.

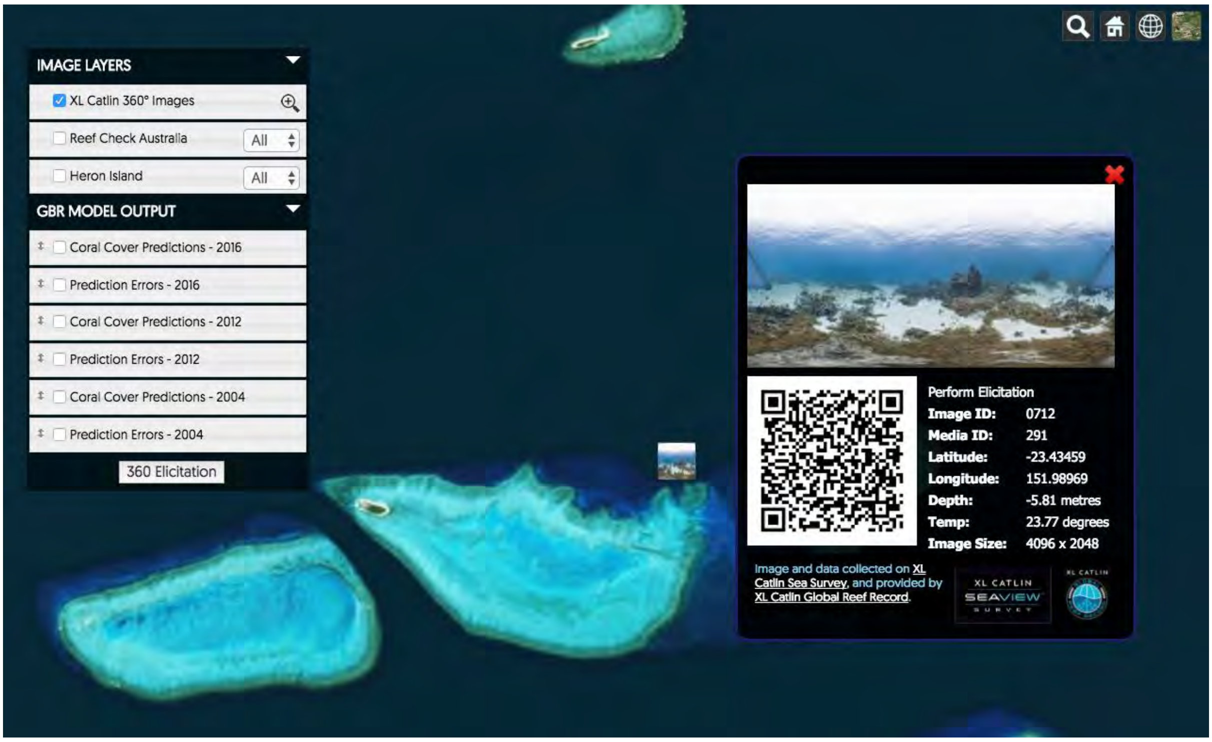


Figure 13. Image layer with Heron Island dataset active and one **360-degree** image selected and highlighted with its QR code.

When the user selects a photo, a partially transparent 'popup' window appears over the map, which can be dragged to relocate its position on the map (Figure *12* and Figure *13*). The window contains the following elements for each photo item selected:

- preview image of the larger 2D or 360-degree image;
- a QR code that is viewed with the VR application, allowing the user to view the image in their headset;
- image metadata pertaining to the location and depth; and
- an image source attribution where the image has been supplied by a third party.

Such a flexible mapping interface allows users to select, drill down and view images. In addition, the presentation of the QR code allows viewers to use the VR application for immersive experience of the 360-degree images and to then provide elicitation information if they so desire. We describe this process later in the user manual in Chapter 2.

1.5.2 Prediction layers

Output results from spatial statistical models executed in the background are also visualised as layers within the map, available via the menu system on the left of the image below. These views are presented as Prediction and Error. The Prediction layer shows the predicted coral cover for a region from the model, the Error layer shows the related prediction error for that location as a colour gradient. We refer the reader to the project report for a detailed explanation of the mathematics behind these models. Here, we will describe how these results can be viewed within our map-based application.

Modelling layers also have the capability to be turned on or off and can be re-ordered through a simple drag and drop interface, allowing layers of interest to be brought to the top of the layer stack, becoming visible. Additionally, any of the modelling layers can be faded in or out through an alpha sliding fader on a per layer basis (Figure *14*).

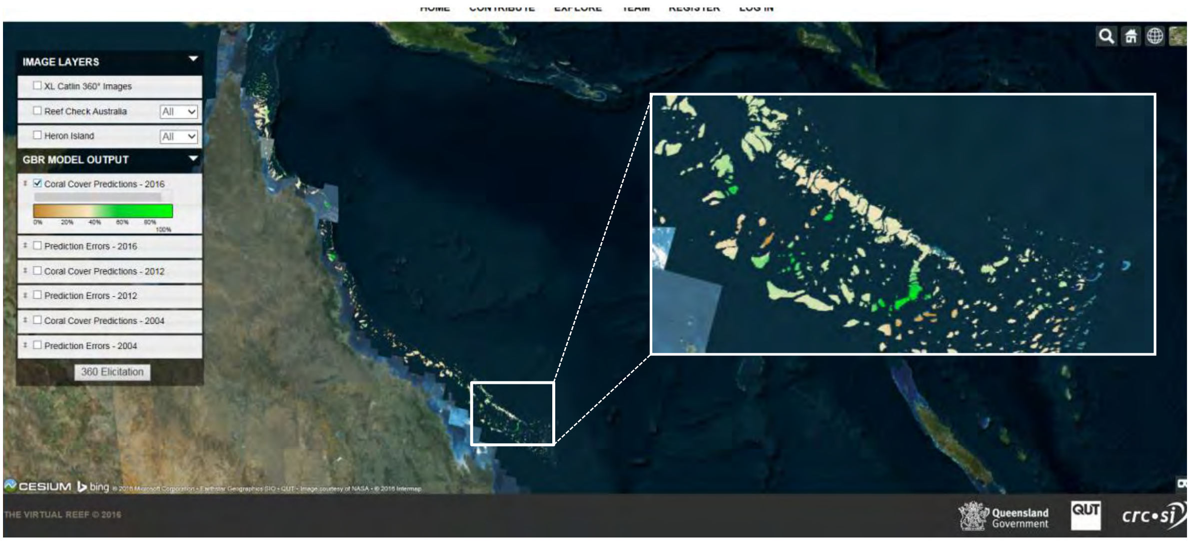


Figure 14. Example overview of model prediction layer for 2016, with a map inset showing a more detailed view of the prediction layer.

In a similar manner to the Image layers, the Model layers are selected in the bottom part of the menu, turning them on in the map view. Below, we now show both the Prediction and Coral cover from the 2016 model shown on the map of Heron Island. In Figure *15* we see the map around Heron Island with the model layers turned off.

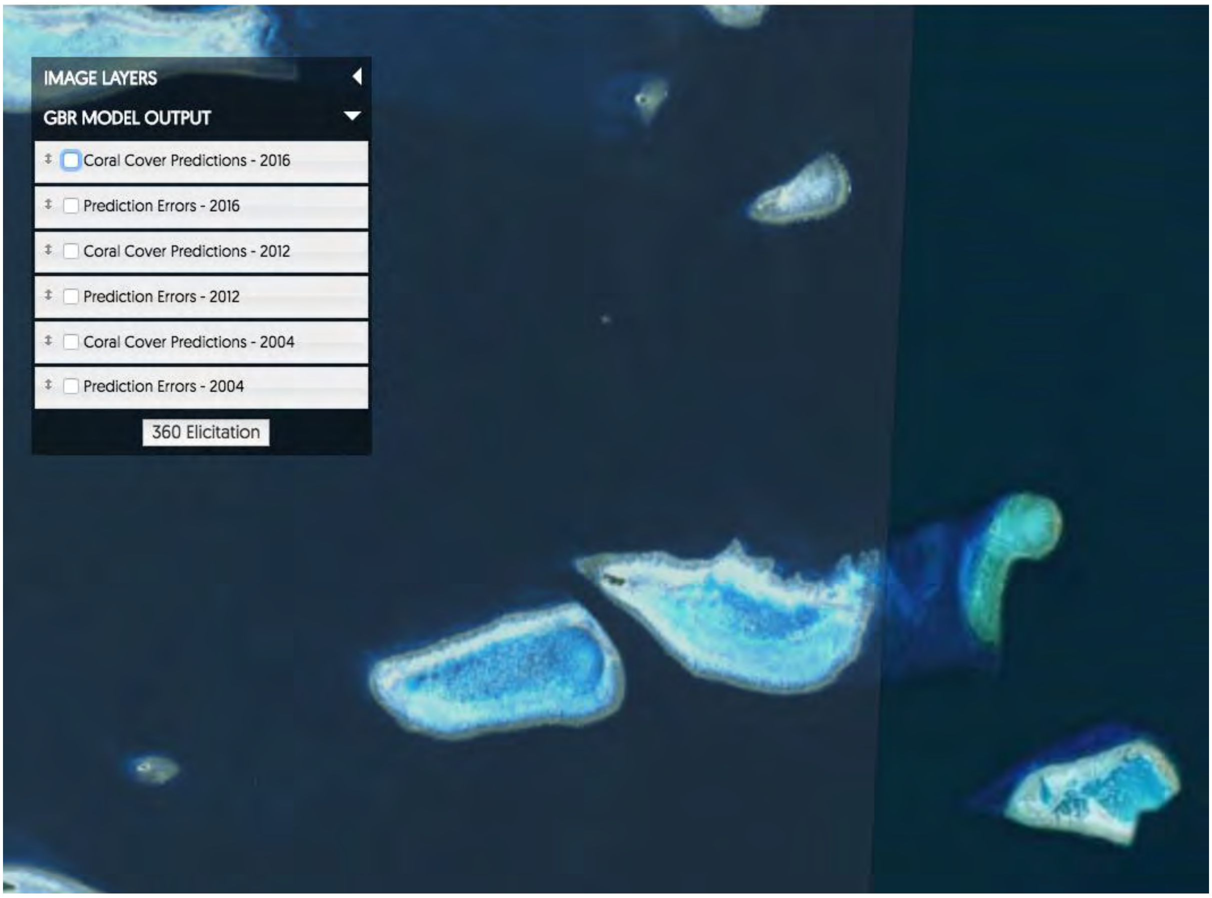


Figure 15. Basic map of Heron Island without any overlaid spatial models.

In Figure *16* we see both the Coral Cover and Error layers have been turned on, but we only see the Prediction layer on the map, with a gradient of colour showing the percentage of predicted coral cover at those locations. Note, the models are not calculated at the same resolution as the mapping imagery, thus the blocky outlines of the colour maps shown in the prediction and error model layers.

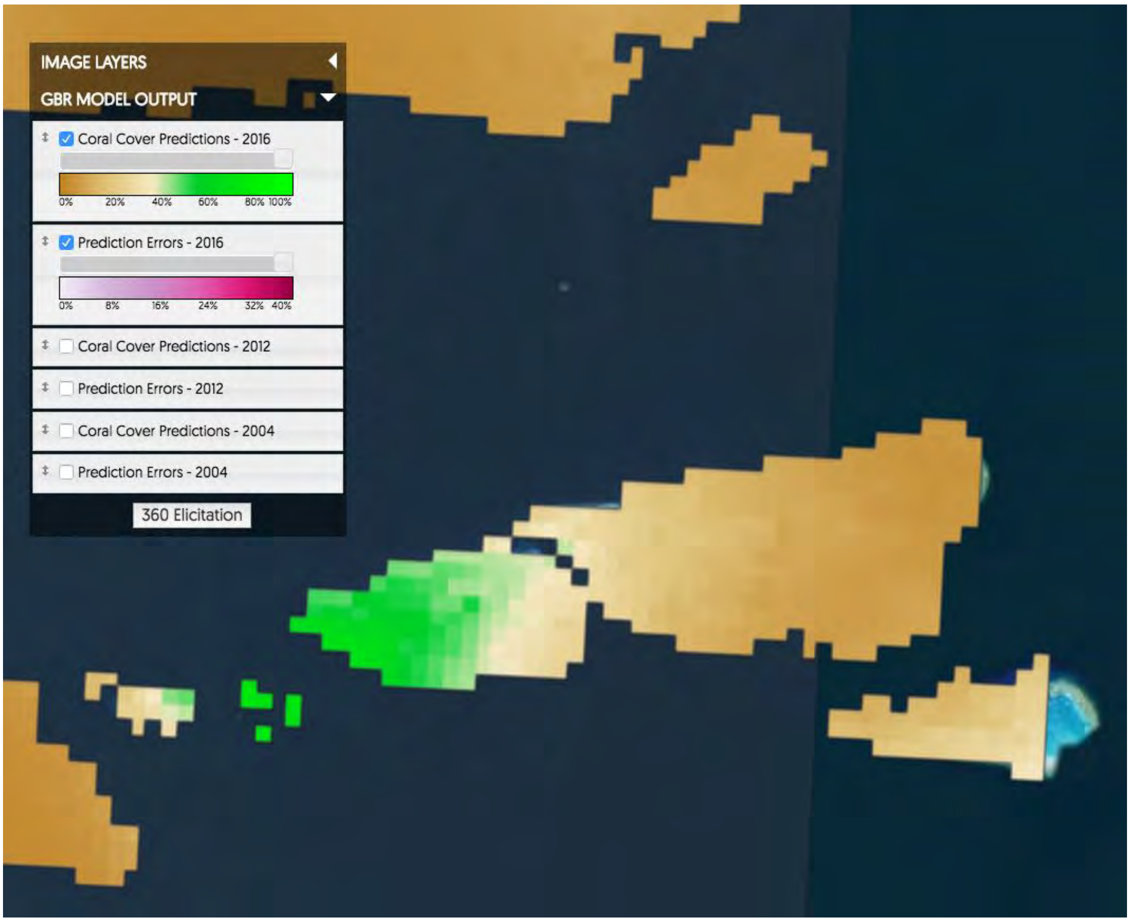


Figure 16. Heron Island map with prediction and error data selected. The prediction data is on top of the layer menu and so is displayed.

In Figure *18* we see the Error layer has been dragged up using the arrowed tab as shown in Figure *17* and is thus the visible map layer.

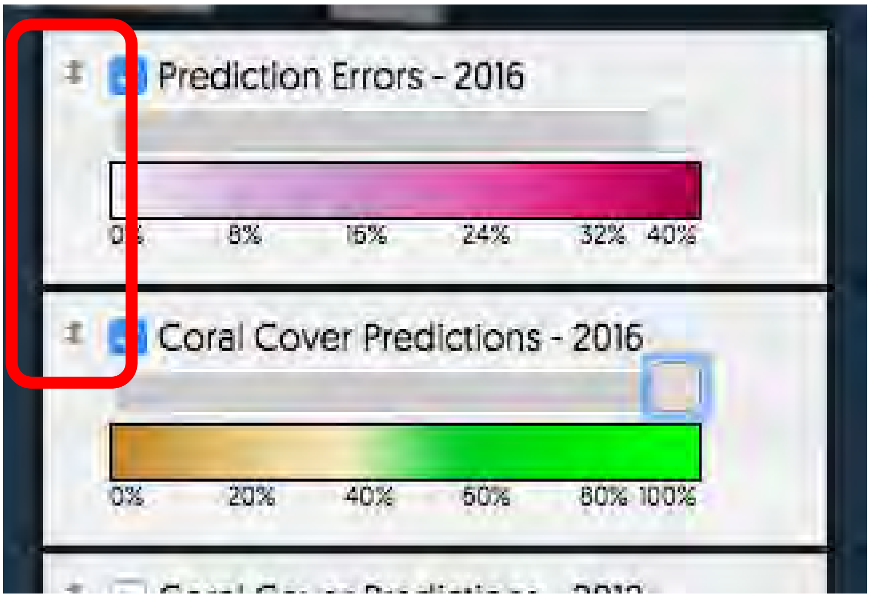


Figure 17. Layer menu with arrows (in red box) giving the ability to drag layers to top to make them active on the map.

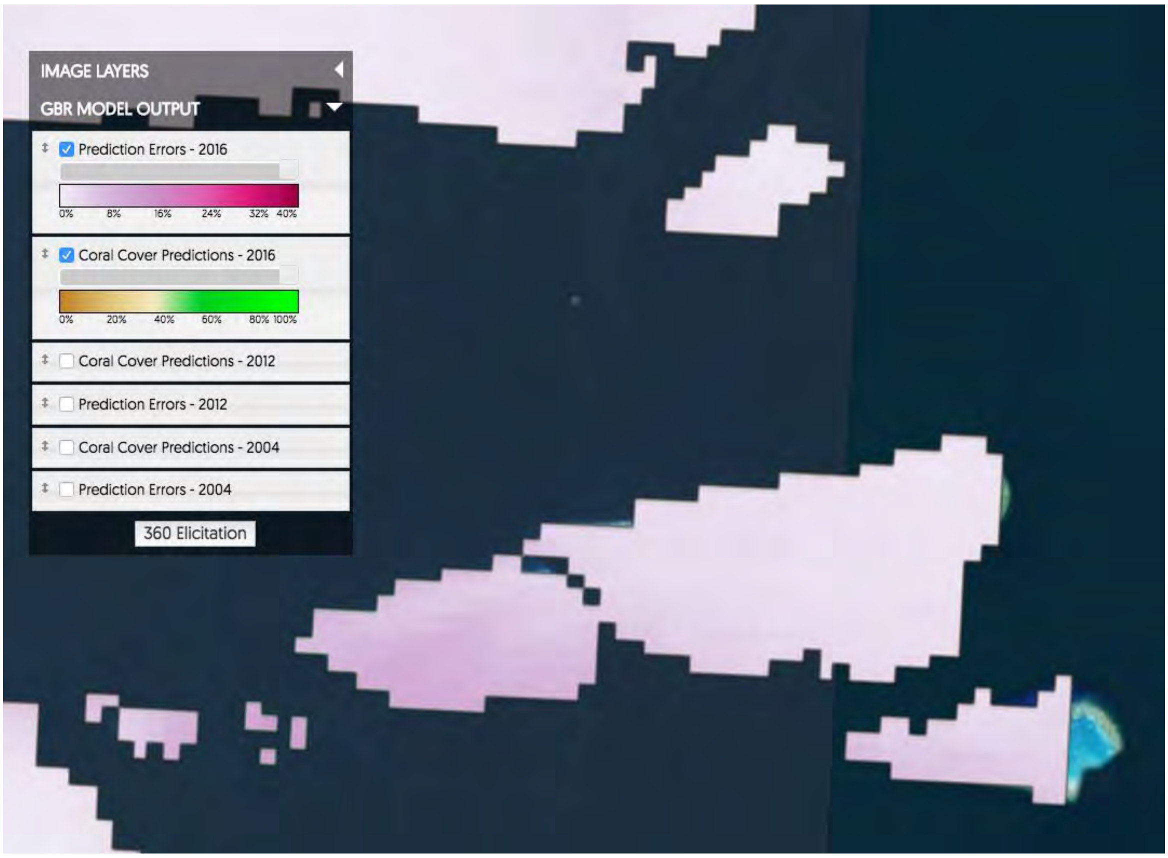


Figure 18. Error layer is on top of the menu and so is displayed on the map.

In addition, the layers can be blended together using the slide bars on the layer menu, as shown in Figure 18. The prediction layer is still on top and active, but has its blending slider at zero, thus the Error layer shows through. Other blending values may be chosen to suit viewing requirements, this example is for explanatory purposes.

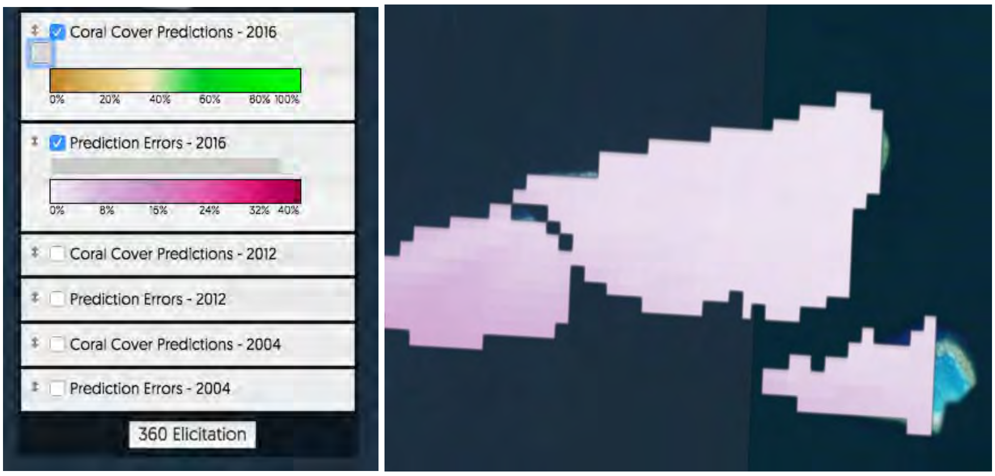


Figure 19. Error layer shows through in this image as the blending values for the prediction layer are at zero.

1.6 Register and Log In

To contribute photos to the service, a user is required to create an account and log in. This is required to both reduce automated image uploading by malicious non-authenticated users, and to identify and eventually weight the quality of users' contributions.

To create an account, a user must only supply a username and password on the registration page from the *Register Menu* option (Figure *20*). Once logged in (Figure *21*), they can use the previously described *Contribute* page to add photos for elicitation. They can also perform elicitations themselves, with their authentication token (UserID) integrated and passed through the QR code to the VR environment.

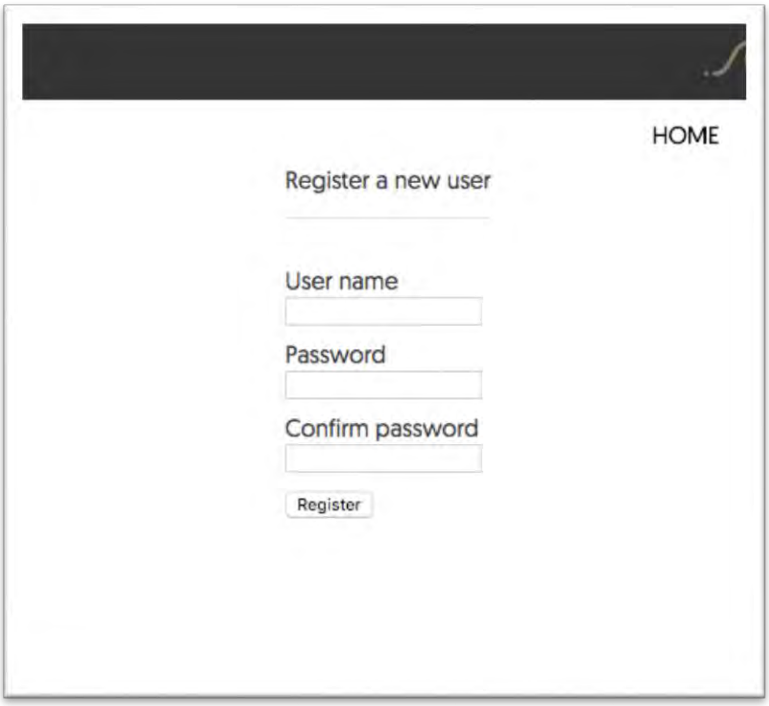


Figure 20. User registration page.

Figure 21. Login page.

Creating a sense of ownership, by allowing a user to see their uploaded photos and elicitation contributions, increases user engagement and subsequently the quantity and quality of the data collected. Once an account is registered and the user logs in, the *Register* menu option changes from *Register* to *My Profile* (Figure *22*). The *My Profile* page, available once the user logs in, displays previous contribution information, enabling users to see how much they have contributed to the project (Figure *23*).

Figure 22. Once logged in the Register menu option changes to include a My Profile option.

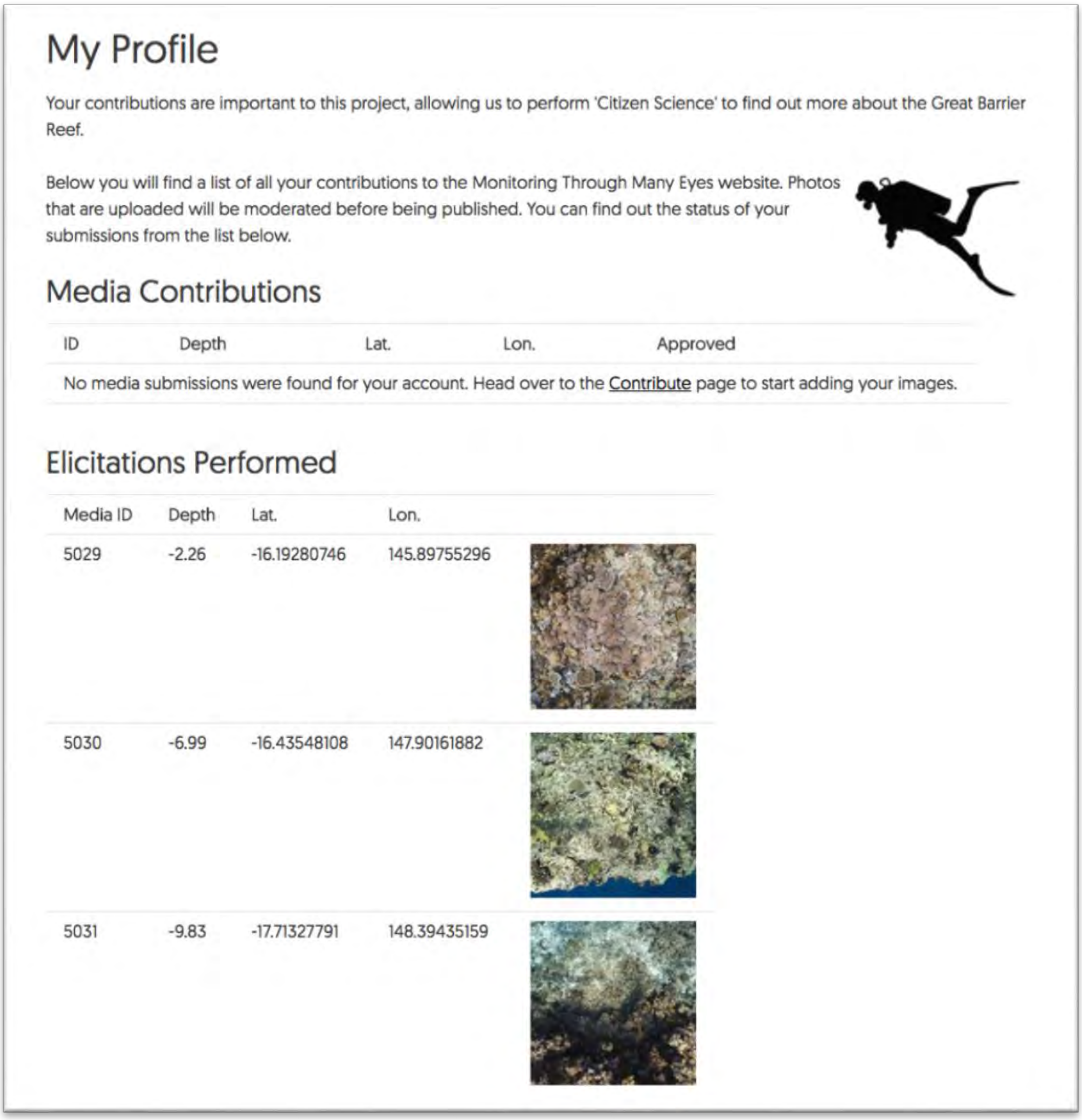


Figure 23. My Profile page from the website showing uploaded images and elicitations performed by a contributor.

1.7 Prototype Website Access

The complete prototype application is currently hosted on the Queensland University of Technology (QUT) network, accessible via QUT's Virtual Private Network (VPN) only. It can be viewed at http://eyesonthereef.qut.edu.au. This version contains proprietary datasets which were used to fit and validate statistical models and data visualisation outputs. Additionally, it contains the upload and membership features.

In addition, a limited version of the website has been released in the public domain, primarily to showcase the use of the QR Code to VR Application mechanic to load and view a licenced selection of both 2D and 360-degree imagery. In addition, users can explore the model outputs within the map. The external website can be viewed at https://www.virtualreef.org.au.

2. The VR Elicitation System

2.1 VR Elicitation Application Overview

The virtual reality (VR) elicitation application is a mobile phone-based application designed to run on Android phones running within a Samsung GearVR headset (Figure *24*). There are two modes of operation that can be accessed within the app; a coral cover annotation elicitation mode and a reef aesthetics survey mode. These modes are detailed in Sections 2.1.3 and 2.1.4.

The VR application supports both standard 2D and 360-degree images for elicitation. 360-degree images are stored in an equirectangular projection, which looks distorted when viewed as a flat 2D image, but looks correct when 'wrapped' onto the inside of a sphere, with the user placed in the centre of that sphere. The user is required to physically look around to view the entire 360-degree image. In contrast, standard 2D images are displayed as a 'virtual cinema screen' with the image presented in front of the user as though on a large screen. The image is slowly scrolled up/down/left/right following the user's head movement, enabling the user to access all parts of the image for elicitation.

Figure 24. Image of GearVR headset which can be used with our VR elicitation components.

2.2 Initiating an elicitation session

The app is started by touching the installed ReefElicitationHCI application icon (highlighted in Figure 25). We assume users are familiar with the basics of orienting and choosing menu options within GearVR environments. Any deviations from normal practice, pertinent to our application, will be described.

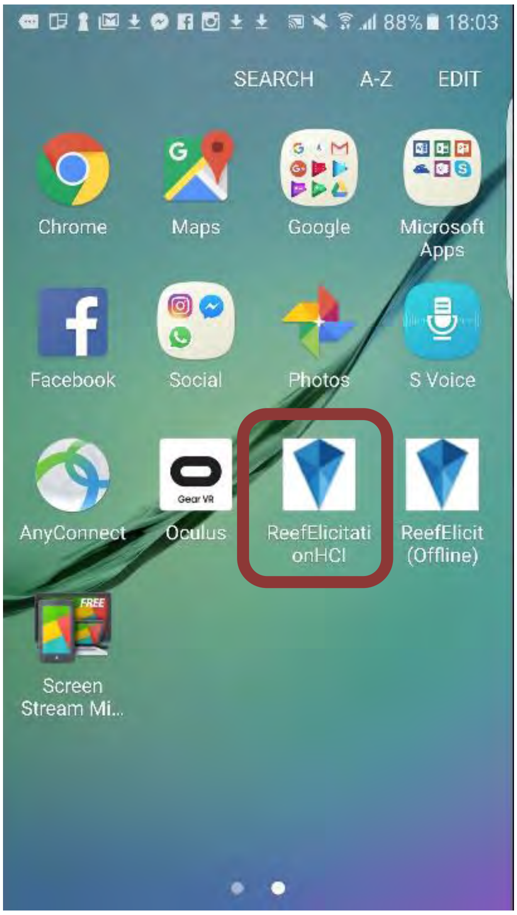


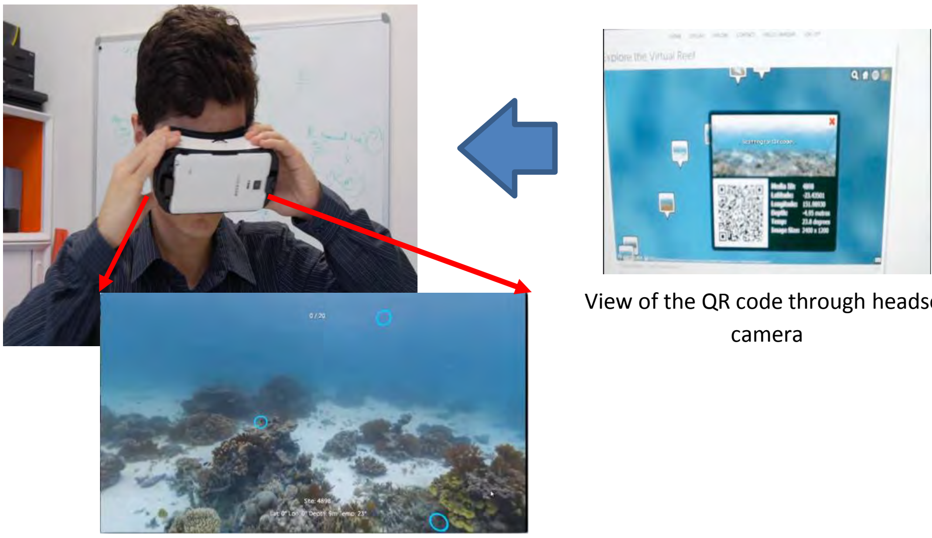
Figure 25. To run the application, choose the highlighted icon, and then insert the Samsung phone into the GearVR.

The choice to do a coral cover or Aesthetics elicitation is then presented (Figure 26). To start ***Coral Cover Annotation*** method, choose the ***Start Annotation*** button. To start the ***Reef Aesthetics Survey*** method, choose the ***Start Survey*** menu button. We will assume the user chooses one of the options for the two elicitation methods we describe in the next two sections.

Figure 26. Choice presented to either perform a Coral Cover Annotation (Start Annotation) or a Reef Aesthetic Survey (Start Survey).

Figure 27. Select the Start button to commence the image selection process.

The application will then get the user to choose the start button to select an image to elicit (Figure *27*). It is *important* that the user should log in and use the website to select the image displaying the QR code. Being logged in will align the elicitation performed to the profile of the user for later analysis, otherwise an anonymous elicitation will be performed. To initiate an elicitation session for a selected image, the user scans the associated QR code for the image using the pass-through camera on the mobile device being used with the VR headset. A pass-through image as seen by the camera is displayed allowing the user to scan the code while looking through the headset (Figure *28*).



View of the QR code through headset camera

Figure 28. Initiating of the elicitation methods by scanning the QR code on the website exploration map, bringing up a 360-degree image in the VR viewer.

Each QR code uniquely represents a reef image linked to a geo-located photo (both standard 2D or 360-degree photos). The QR encodes a string which maps to a unique image (i.e. a MediaID) and associated metadata, and the User ID of a registered user. Once the image is loaded the user will be placed inside the selected 360-degree image and may perform the elicitation previously selected. We describe these in turn.

2.2.1 Coral cover annotation

The Coral Cover Annotation mode has been developed to estimate the percentage of coral cover visible within each image. This is achieved by asking the user to classify a replicable pseudo-random scattering of 20 elicitation points (shown as green circles in the 360-degree image) as one of six different categories (coral, algae, sand, other, water or unknown). The user brings up the classification menu by selecting a circle in the scene and then moving their head orientation to choose a menu item. In Figure *29* the user has classified the circle region as being Coral. The six categories are mutually exclusive and only one option can be selected. The example output data below represents each of these as a single value between 0 and 5 (e.g. 0 = Unknown, 1 = Coral, 2 = Algae, 3 = Sand, 4 = Other, 5 = Water).

Figure 29. Coral cover elicitation interface menu.

Users should repeat the above classification process for all the 20 points distributed within the 360-degree image. Once completed (a display at the top shows progress as a number over 20, e.g. 15/20) the user will be asked to submit their results (Figure *30*).

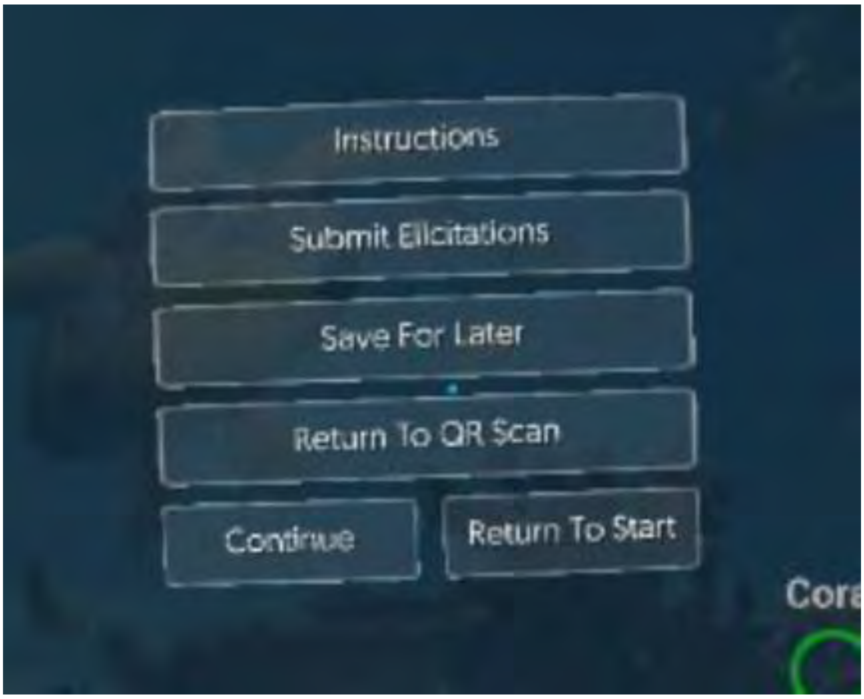


Figure 30. Coral estimate submission menu.

The user then may annotate as many images as they wish by repeating the above process with other website 360-degree images.

2.3 Prototype VR Application Access

The mobile application has been developed using the Unity game engine environment with additional scripting written in the C# language. The current implementation has focused on the Android-GearVR combination of technologies, primarily to take advantage of the touch button on the side of the GearVR headset. Support for the GearVR headsets is also conveniently a built-in feature of the Unity platform. Future development could relatively easily expand upon this to also support iPhone and newer Google mobile devices, across the range of Google Cardboard and Daydream compatible VR headsets.

One restriction of GearVR mobile applications is the requirement to sign each mobile device running the application with a unique Oculus signature. This signature file is generated on the Oculus developer portal website and placed within the Unity project before the application is built and deployed to the mobile device. This restriction prevents us from easily distributing the application and deploying onto phones, without using the Unity build and deployment process. This can only be avoided by submitting the application to the Oculus VR online store, which was not an option for this stage of the project. More information about application signing can be found here https://developer3.oculus.com/documentation/publish/latest/concepts/publish-mobile-app-signing/. We are happy to provide a binary of the Android application on request.

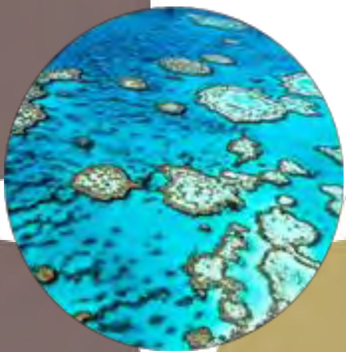
3. Acknowledgements

We would like to acknowledge the Cooperative Research Centre for Spatial Information and the Queensland Department of Natural Resources and Mines for providing funding for this research.

The team also collaborated with citizen science and research organisations to conduct our experiments and receive contributions of data and images. We would like to give a big thanks to our collaborators/contributors – this project would not be possible without them.

- Australian Institute of Marine Science (http://aims.gov.au/)
- Reef Check Australia (www.reefcheckaustralia.org/)
- University of Queensland (UQ) Remote Sensing Research Centre (https://www.gpem.uq.edu.au/rsrc)
- UQ Global Change Institute (http://www.gci.uq.edu.au/)
- XL Catlin Global Reef Record (http://globalreefrecord.org/home_scientific)

Monitoring Through Many Eyes: Spatially enabling people to protect the Great Barrier Reef



Stage 2 – Report 4/4

Modelling document

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10th May 2017

About us

The Monitoring Through Many Eyes project is a multidisciplinary research effort designed to enhance the monitoring of the Great Barrier Reef. The project aims to create a virtual reef by geotagging underwater photos and videos contributed through citizen science. These will be used to create immersive environments that will help to improve estimates and predictions of the health of the Reef. Our mission is to deliver new know-how in visualisation and spatial statistical modelling, new spatial products, and a new avenue for the public to engage in monitoring the reef.

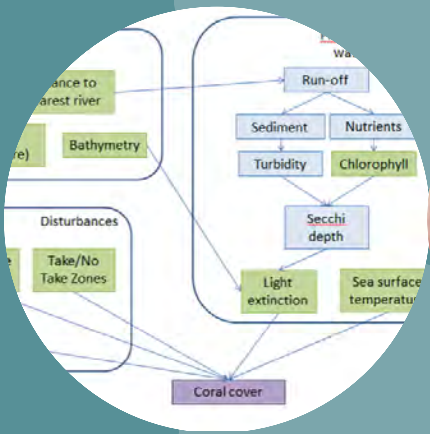
Table of Contents

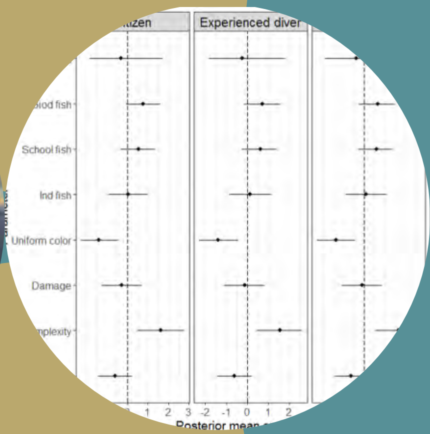
Introduction

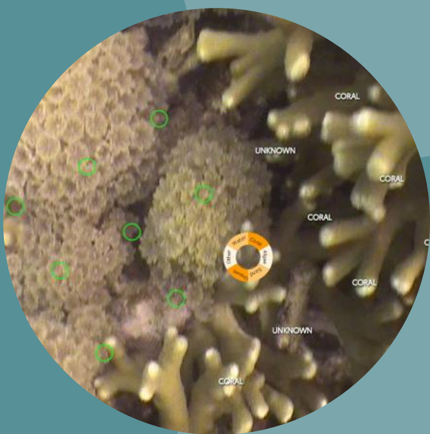
This document describes the statistical analyses undertaken in the modelling component of the Monitoring Through Many Eyes project (Figure 1). The primary study, the coral cover model, describes the modelling of the proportion of coral cover as a function of several explanatory variables and different sources of data over the entire Great Barrier Reef (GBR). The goal of this study was to showcase the benefits of the integration of data from different professional surveys of coral reefs and citizen science programs within the same statistical framework. A supplementary study, the reef aesthetics experiment, was also performed during the project. In this experiment, 360-degree images of the GBR were used to elicit information from different groups of people about their visual and emotional perceptions of multiple reefs in varying conditions. This second study was outside the scope of the original project but was contributed as additional research to demonstrate the power of the virtual reality (VR) technology.

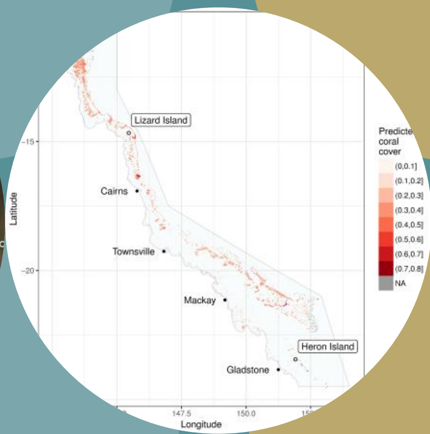
Figure 1 Overview of the Monitoring Through Many Eyes project components.

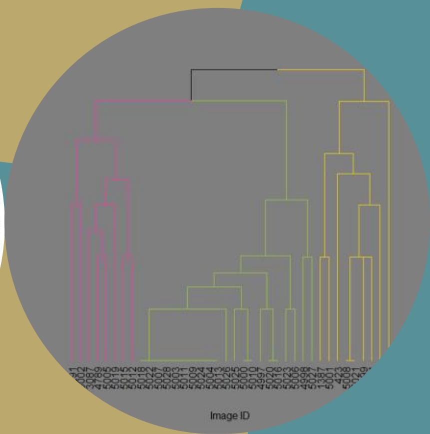
1. Coral cover model











1.1 Introduction

A major aim of the Monitoring Through Many Eyes project was to create a predictive visual environment to better monitor the health of the Great Barrier Reef (GBR). We combined crowd-sourced imagery with existing spatial information products and employed advanced spatio-temporal statistical models to predict coral cover throughout the GBR. As part of this process, we developed new interactive software tools to elicit estimates of coral cover from underwater image annotations performed by citizens. We then developed statistical methods that allowed us to use the elicited responses (e.g. coral cover estimates) and other extant geo-referenced information to enhance spatial models that were applied to the whole-of-the reef. This section describes the modelling approach we developed to quantify the uncertainty in data from different sources, such as professional monitoring programs and citizen science data, before integrating these diverse data sources into a single predictive model.

1.2 Methods and Materials

1.2.1 Coral cover measurements

Coral cover represents the proportion of the benthic zone which is covered in hard corals. These estimates are typically collected in transects consisting of individual images, which are then either manually annotated or automatically classified using software such as CoralNet (Beijbom et al. 2015). We used coral cover data from a number of different sources including the: XL Catlin Seaview Survey (González-Rivero et al. 2014); Great Barrier Reef Long Term Monitoring Program (LTMP) and the Reef Rescue Marine Monitoring Program (MMP), conducted by the Australian Institute of Marine Science (AIMS); the Heron Island survey, by Roelfsema (2012); and the Capricorn and Bunker group survey conducted by the Remote Sensing Research Centre (RSRC) at the University of Queensland (UQ). Each dataset provided multiple estimates of coral cover, but there were differences in the scale of the estimates and the estimation method (Table 1).

Table 1 Differences in the coral cover data sources included the scale of the coral cover estimate, the number of images the estimate was based on, the extent of each individual image, the classification method, and the number of annotations per image.

Source	Number of reefs	Scale	Number of images	Image extent (m^2)	Classification method	Annotation points
Capricorn and Bunker group	13	Image	1	4.00	Annotated	24
Heron Island	1	Image	1	4.00	Annotated	24
XL Catlin	32	Image	1	2.00	Automated	100
LTMP	47	5 × 50m transects	40	1.00	Annotated	5
MMP	32	5 × 20m transects	32	1.00	Annotated	5
Reef Check	60	Image/person	1	0.12	Annotated	20

The XL Catlin Seaview survey dataset (hereafter referred to as Catlin) contained 42386 geo-located images which were taken in 2-3m intervals along unique transects varying in length from 1.6km to 2km (González-Rivero et al. 2014). A total of 89 transects within 33 reefs were surveyed within the GBR at a constant depth of 10m. Images were taken by professional staff with cameras equipped with geographic positioning systems (GPS), which provided the exact location of each image. The Catlin Survey uses a combination of manual and automated procedures to derive an estimate of the proportion of coral sub-categories (Table 1; Beijbom et al. 2015). We were provided with a dataset containing the coral sub-category cover estimates (rather than the images), which we aggregated to obtain an estimate of hard coral cover in each image (Table 2).

The LTMP program was designed to monitor benthic communities over time across 6 sectors of the GBR. Within these sectors the LTMP samples three reef habitats defined by the position of reefs on the continental shelf (i.e. inner -, middle-, and outer-shelf positions), except for the Swain (middle- and outer-shelf) and Capricorn-Bunker (outer-shelf) sub-regions, in which fewer habitats are represented (Sweatman et al. 2005). The survey is spatially replicated on two to four reefs per habitat and sub-region, with each reef sampled at three distinct sites. A total of 141 sites were sampled at a depth of 6-9m annually from 1992 to 2004, and then biennially from 2005 to 2016, yielding 16851 coral cover estimates to be included in this analysis.

Each 'site' in the LTMP is composed of five permanent photo (prior to 2006) and video transects (from 2006), with a width of 1m and a length of 50m, with 10m intervals between transects. Images were taken at 1m intervals along a transect. Then 40 random images were selected for manual annotation by marine scientists, who were asked to classify five points per image (Jonker et al. 2008). Coral cover estimates are reported at the site scale, with the latitude and longitude of the first image in the transect used to identify the spatial location. The MMP survey adheres to the same data collection technique, except that 5 20m transects are sampled and 32 images are randomly selected for annotation. In addition, sampling is focused on the inner reefs of the GBR, whereas the LTMP focuses on the outer reefs. The MMP dataset consisted of 6068 coral cover estimates, which were collected from 32 reefs between 2005 and 2016.

Images at Heron Island reef were collected in 2007 (3587 images) and 2012 (5014 images) by the RSRC at UQ. Images were taken in 10-100m intervals along 21 transects in 2007 and in 24 transects in 2012. Features from the images were classified into 10 categories of benthic cover and several sub-categories (Table 2). We aggregated these coral sub-categories to obtain an estimate of the total proportion of coral cover per image. The Capricorn and Bunker group of reefs were also surveyed by the RSRC in 2014 using the same methodology as the Heron Island survey, and 9476 of these images and coral cover estimates were used in this study.

Table 2 Benthic functional groups and sub-categories used in the Heron Island and XL Catlin Seaview Surveys.

Survey	**Category**	**Sub-categories**
Heron	Coral	Live Branching Fine
		Live Branching
		Live Encrusting
		Live Digitate
		Live Tabular
		Live Sub Massive
		Live Foliose
		Live Free Living
		Live Massive
Catlin	Coral	Acroporidae
		Favidae-Mussidae
		Pocilloporidae
		Poritidae
		Other

1.2.2 Reef reference layer

A reference raster with a spatial resolution of 0.005 decimal degrees (dd) was created, covering the extent of the reefs in the GBR. The GBR Features shapefiles (GBRMPA 2014) were used to identify reef areas within the GBR, which were buffered by 1km and converted to raster format. The resulting reference raster was then used to aggregate and align other covariate rasters. The resolution of 0.005 dd was chosen as it was comparable to the existing resolution of the covariate rasters (Table 3) and produced a reasonable cell count for modelling and visualisation (85529 cells).

1.2.3 Covariate data

A number of physico-chemical, topographic and disturbance variables were included in the model to account for direct and indirect sources of variation in coral cover (Figure 2). These variables were selected in consultation with marine scientists from AIMS. The depth (bathymetry) was included in the model both directly and indirectly. Light extinction was derived from both depth and secchi depth, according to the methodology described by the Joint Nature Conservation Committee (2012), with a value of 1 representing perfectly clear water and 0 representing no light penetration (Table 3).

The Euclidean distance to river mouth (km) was derived in R (R Core Team 2016) from the reference raster and a shapefile of river mouths provided by James Cook University. No take zones were derived from the GBR Features Marine Park Zoning shapefile (GBRMPA 2014). The "Pink", "Green", "Orange" and "Olive green" zones were coded as 1 (no take zones), and all other zones were coded as 0. Crown-of-Thorns starfish (COTS) prevalence was derived from the eAtlas spatial interpolation of the AIMS LTMP Manta Tow Surveys (Sweatman et al. 2005), and log-transformed for inclusion in the model.

The rasters were resampled to match the spatial resolution of the reference raster (0.005 dd). Values at the relevant spatio-temporal coordinates were extracted for inclusion in the model as covariates. After aggregating to 0.005 dd and extracting covariate values, the data were projected to UTM coordinates for analysis. Hence geographic coordinates were used here to locate objects, but not to analyse relationships and distances between them (Dana 2008). Geo-processing operations were performed in R with the sp (Pebesma and Bivand 2005), maptools (Bivand and Lewin-Koh 2016), raster (Hijmans 2016), and rgeos (Bivand and Rundel 2016) packages, and ArcGIS (ESRI 2016).

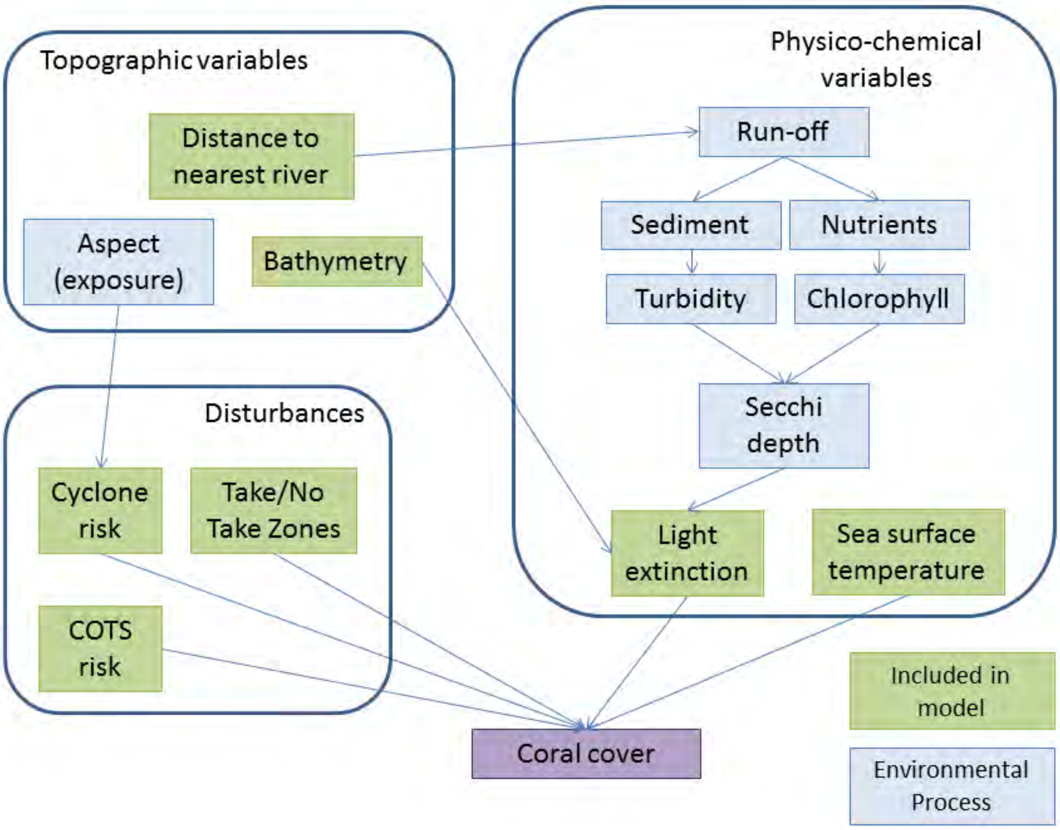


Figure 2 Conceptual model showing the direct and indirect influence of variables on coral cover.

GBR Management Zones and Marine Bioregions were rasterised, based on GBR Features shapefiles (GBRMPA 2014) and converted to categorical explanatory variables. These accounted for, respectively, North-South gradients in coral cover and the difference between inner and outer-shelf coral cover. The shelf position covariate was derived in ArcGIS (ESRI 2016) from the LOC_NAME attribute in the Marine Bioregions of the Great Barrier Reef (GBRMPA, 2014) shapefile. Polygons with a LOC_NAME attribute containing the words “Outer”, “Coral Sea”, “Hard Line” or “Deltaic” were classified as outer-shelf reefs (code as 3). Polygons with a LOC_NAME attribute containing the word “Mid” were classified as middle-shelf reefs (coded as 2). All other polygons were classified as inner-shelf reefs (coded as 1). The polygons were converted to a raster format, with the cells assigned values according to the shelf position codes above. A five cell buffer was attached to reef cells in the raster.

Table 3 Covariates that were included in the coral cover model. The spatial resolution is given in decimal degrees.

Covariate	Description	Source	Spatial Resolution	Temporal Resolution
Bathymetry	Depth below sea level (metres)	Beaman (2010)	0.001	As measured in 2010
Crown-of-Thorns (COTS) Starfish	Modelled number of COTS per tow based on the AIMS Manta Tow survey	(Sweatman et al. 2005)	0.020	Averaged 1986-2005
Cyclone risk	Mean cyclone frequency per 100 years	Wolff et al. (2016)	0.044	Averaged 1970-2011
Distance to river mouth	Distance from the nearest major river mouth on the QLD coastline	E. Teixeira da Silva and S. Lewis, James Cook University (personal communication)	0.005	-
Light extinction	Attenuation coefficient (0-1): proportion of light penetrating the water column to the sea floor	Beaman (2010), De'ath (2007)	0.005	Bathymetry in 2010, secchi depth averaged 1992-2006
Management areas	Great Barrier Reef management regions (1-4)	GBRMPA (2014)	0.010	Great Barrier Reef Zoning Plan 2003
No Take Zone	Protected areas where no fishing is allowed. 1 = no-take, 0 = otherwise	GBRMPA (2014)	0.005	Great Barrier Reef Zoning Plan 2003
Sea surface temperature anomaly	Difference between measured sea surface temperature (SST) and monthly long-term mean SST (°C)	BOM (2014)	0.020	Annual averages for 2002-2016
Shelf position	Position of reefs on the continental shelf; 1= inshore/inner shelf; 2 = middle shelf; 3 = outer shelf	GBRMPA (2014)	0.005	Great Barrier Reef Zoning Plan 2003

To account for sparsity of data in particular zones and bioregions (e.g. the LTMP only measures outer reefs), the Management Zones were coded as “Southern” (1, Mackay/Capricorn Management Area), “Central” (2, Townsville/Whitsunday Management Area) and “Northern” (3, Far Northern Management Area, Cairns/Cooktown Management Areas). The Inner and Middle reef bioregions were combined as “Inner”.

1.2.4 Citizen Science data

Citizen science data were sourced from Reef Check Australia (http://www.reefcheckaustralia.org), a citizen science organisation working to monitor the GBR. Reef Check recruits and trains volunteer divers to perform underwater visual reef surveys by capturing video along a series of transects within the GBR.

Reef Check images were originally supplied as video footage on MiniDV tapes, taken during surveys within the GBR. A selection of 13 DV tapes, representing videos of reef surveys from Magnetic Island to Osprey Reef, from 2003 to 2009, were digitised into video files. The videos each contained between 25 and 120 minutes of video from at least one dive site. The dive sites were, in turn, broken up into four 20m transects separated by 5m. At the beginning of each site, the diver indicated which transect out of four was being surveyed by holding up fingers or a slate with the same information. Each video was manually searched for transect start and end points and the timestamps were recorded alongside the reef name, site number, the coordinates of that reef, and the date of the survey, using a metadata table provided by Reef Check.

Images were extracted from the videos by pulling out frames at set times. For each transect, 1000 timestamps were generated from a 1D Poisson point process and 5 of these timestamps sampled while ensuring that at least 10 seconds had elapsed between them; thus ensuring that the same area was not present in consecutive images. After extraction, images were deinterlaced and an unsharp mask applied in Adobe Photoshop CC 2015 in order to provide an image free from distortion. The position of each image was estimated based on the timestamps of the sampled frames, and information about the start position and bearing of the transects. This provided a way to locate and display each image on a map.

1.2.4.1 Elicitation from Citizen Science data

An elicitation tool was developed to allow users to browse a map of the GBR and select images for annotation. A template of 20 elicitation points was generated as an overlay for each image. When a user opened an image in the elicitation tool, the points were displayed as a green circle. If the user hovered their mouse over the point, a menu containing six annotation categories was revealed, which allowed the user to classify the annotation point into water, coral, algae, sand, unsure, and other (Figure 3).

Once all 20 points were annotated, the user submitted the annotations to the database, where the image's media identifier (ID), latitude and longitude, an elicitation identification (ID) number (for each point in the image), each point's horizontal (u) and vertical (v) position and annotation label, and the user ID for the person providing the annotation was recorded. For an elicitation of an image, by a user, the coral cover estimate was based on the number of points labelled "coral" as a fraction of the number of points labelled as something other than "unsure" or "water". The involvement of citizen scientists is detailed further in section 1.3.1.

Figure 3 Partially annotated citizen science image in the 2D elicitation system, derived from Reef Check Australia videos.

1.2.5 Statistical modelling

1.2.5.1 Deriving weighted coral cover estimates

There were differences in the number of locations at which data were collected, the number of images per aggregation cell and the number of elicitation points per image across the multiple professional surveys (Catlin, Capricorn and Bunker group, Heron Island, MMP, and LTMP) and citizen science surveys (Table 4). In addition, there were intrinsic and extrinsic factors that affected the coral cover classification. Intrinsic factors included the image's areal extent (a combination of focal length and distance to reef), the camera orientation, and the haziness of the image (a combination of water quality and camera quality). Extrinsic factors included the number of annotation points in the image and whether the annotator was a software tool, such as CoralNet (Beijbom et al. 2015), or a marine scientist or citizen scientist.

Table 4 Weights for the professional survey data, which include the XL Catlin Seaview Survey, the Capricorn and Bunker group (CB Group), the Heron Island surveys, and the Long-term Monitoring Program (LTMP) and Reef Rescue Marine Monitoring Program (MMP). Weights for image orientation and blur have been omitted because they were set to 1 for all images.

Source	**Extent ($w_{e_{js}}$)**	**Number of points (w_{n_j})**	**Images per coral cover estimate (w_{N_s})**	**Coral cover estimate weight (w_{js})**
Heron/CB Group	1.000	10	1	10
Catlin	0.5	10	1	5
LTMP	0.25	5	40	200
MMP	0.25	5	32	160

1.2.5.2 Citizen elicited images

Image-specific weights were derived for the citizen science data by considering the image haziness, the annotator accuracy, physical extent and orientation of the image, and the number of points used to elicit the coral cover in an image. The weights associated with the annotation of image j, within survey s, annotated by person p were therefore a product of the following sub-weights:

$$w_{jps} = w_{e_{js}} w_{b_{js}} w_{o_{js}} w_{n_{jps}} w_{a_p}.$$

Each component contributing to w_{jps} is described in detail in the following sections.

1.2.5.2.1 Image extent

For each source of images (survey), an extent weight, $\mathrm{w}_{\mathrm{e_{js}}}$, was derived based on an estimate of the physical area captured by the camera. In this study, the Heron Island and Capricorn and Bunker groups images had the largest extent, $4\mathrm{m}^2$, and therefore for these images $\mathrm{w}_{\mathrm{e_{js}}} = 1$ (Table 4). The extent weight of the images from the remaining surveys was based on the ratio of the approximate area of these images to the Heron Island/Capricorn and Bunker images. The LTMP and MMP images were estimated to be $1\mathrm{m}^2$, and the Catlin images were approximately $2\mathrm{m}^2$. The Reef Check citizen science images had a much smaller extent. A measuring tape could be seen in the images, which were approximately$0.12\mathrm{m}^2$. We enforced a lower bound on the image extent weight at 0.05 to ensure that images with small extents do not get down-weighted to the point where they cannot affect the overall coral cover estimate, regardless of how many images are provided. Therefore, the extent weight was set to $\mathrm{w}_{\mathrm{e_{js}}} = \max(0.05, \mathrm{A_j}/4)$, where A_j is the areal extent of the image.

1.2.5.2.2 Image orientation

For each image in each of the surveys, an image orientation weight, $w_{o_{js}}$, and blurriness (i.e. image clarity), $w_{b_{js}}$, were specified to demonstrate that these image characteristics could potentially be accounted for in the weighting scheme. However, in this case the orientation of all professional and citizen science images was straight down, perpendicular to the surface of the water, and so $w_{o_{js}} = 1$ for all images. It would also be desirable to make sharp images more influential than blurry ones when coral cover is estimated. The blur weights were set to 1 for all images in this model, but there may be opportunities to automatically assess image blurriness for incorporation into the weighting scheme in future models.

1.2.5.2.3 Annotator properties

Prior to annotating the images, team members (acting as citizens) were asked to read through a training document which highlighted the differences between hard coral, soft coral and other morphologically similar organisms. A training set of 20 Catlin images was used to assess each user's ability to accurately identify coral at the same 20 elicitation points by comparing their annotations to those of a marine scientist. A classification accuracy measure was used as a weight factor representing user annotation accuracy, w_{a_p}, defined as the average accuracy, following Sammut and Webb (2010), across that user’s elicitations,

$$w_{a_p} = \frac{1}{|\mathcal{J}_{ps}|} \sum_{j=1}^{|\mathcal{J}_{ps}|} \frac{\mathrm{TP}_{jps} + \mathrm{TN}_{jps}}{\mathrm{TP}_{jps} + \mathrm{TN}_{jps} + \mathrm{FP}_{jps} + \mathrm{FN}_{jps}},$$

where TP_{jps} is the number of true positives identified by person p in image j, TN_{jp} was the number of true negatives and similarly FP_{jp} and FN_{jp} were the false positives and negatives for each image and person, respectively. The set $\mathcal{J}_{ps}$ represents the collection of images from survey s annotated by person p. For data from a professional survey, $w_{a_p} = 1$, reflecting the increased capacity of computer software or expert marine scientists to identify hard corals.

1.2.5.2.4 Annotation points in each image

Citizens were asked to annotate 20 points per citizen science image. Individual responses labelled as “unsure” or “water” were removed from the analysis because they cannot be considered “coral” or “not coral” features. Thus, the number of annotations per image for each annotator, $w_{n_{jps}}$, was sometimes less than 20.

1.2.5.2.5 Coral cover estimates

The coral cover estimate for participant p's annotation of image j from survey s was therefore the number of points, indexed k, they labelled “coral” out of the total number of points that they labelled as other than “unsure” or “water”, $w_{n_{jps}}$,

$$y_{jps} = \frac{1}{w_{n_{jps}}} \sum_{k=1}^{w_{n_{jps}}} I\left(y_{jpsk} = \text{"coral"}\right),$$

with $I(\cdot)$ an indicator function and y_{jpsk} the annotation category label for point k in image j from survey s by user p. The total weight allocated to image j in survey s as a result of P participants annotating it was taken to be the sum of the weights associated with each participant annotating it,

$$w_{js} = \sum_{p=1}^{P} w_{jps},$$

and so the coral cover estimate for image j in survey s was the weighted average of the coral cover estimates derived by each participant,

$$y_{js} = \frac{\sum_{p=1}^{P} w_{jps}\, y_{jps}}{\sum_{p=1}^{P} w_{jps}}.$$

As more participants contribute coral cover estimates of image j in survey s, the total weight, w_{js}, increases and the weighted average will converge.

1.2.5.3 Professional monitoring data

The professional survey data were aggregated to the reference raster cells. Therefore, the amount of information within the cells was different depending on the various survey designs and annotation procedures (Table 4). For example, the LTMP and MMP data were already aggregated to the transect level when we obtained them and only a single estimate of coral cover was provided for each transect; while the other professional survey sources provided data at the georeferenced image level. The extent, orientation, and blur of the images were accounted for in the same way they were for the citizen science images. However, it was also necessary to account for the number of annotation points and the geographical density of images used to estimate coral cover for the transect-level LTMP and MMP data. The coral cover estimates provided by the LTMP and MMP surveys were based on 40 and 32 images, respectively (Tables 1). Thus a weight, w_{N_s}, was defined for the number of images comprising each coral cover estimate (Table 4). This weight was set to be 40 for LTMP, 32 for MMP, and 1 otherwise.

The total number of points annotated on an image, whether by software or a marine scientist, was included as w_{n_j}. For the Heron Island and Capricorn and Bunker group surveys, 24 points were used for manual annotation, but only 5 annotation points were used for each LTMP and MMP image. In contrast, images sourced from XL Catlin were automatically annotated by the CoralNet software (Beijbom et al. 2015). The number of points required to obtain an automatic estimate of coral cover which is comparable to a manually annotation by an expert is 10 (Beijbom et al. 2015), and manual annotation of additional points within an image does not provided a substantially higher quality estimate of coral cover for an individual image. In addition, there may be errors associated with automatic image classification and so the number of annotation points allocated to the Catlin, Heron Island and Capricorn Bunker coral cover estimates was $w_{n_j} = 10$ (Beijbom et al. 2015).

The orientation and extent weights described the physical area of the reef contained in each image, and the number of annotation points described how much information had been extracted from the images. Including a weight that represented the number of images used in the LTMP $(w_{N_s} = 40)$ and MMP $(w_{N_s} = 32)$ surveys additionally up-weighted these data to account for the fact that the measurements were aggregated over multiple images. Thus, the weights associated with each estimate of coral cover, *j*, from a survey, *s*, were $w_{js} = w_{e_{js}} w_{b_{js}} w_{o_{js}} w_{n_j} w_{N_s}$. The professional survey weights are shown in Table 4. The lower bound of these weights is 0, which indicates that an image contains no information about coral cover; as would be the case if it was extremely blurry or oriented away from the reef.

1.2.5.4 Data aggregation

The weights described above provided a way to aggregate the various data sources into image-level estimates of coral cover. However, these observations still needed to be spatially aggregated to the reference-raster cell level for each source and year. We accomplished this by calculating the weighted mean and total weight for the collection of images, $\mathcal{J}_{its}$, that were contained within a cell, by source and year. The weighted mean was

$$\overline{y}_{its} = \frac{\sum^{j\in\mathcal{J}_{its}} w_{js} y_{js}}{\sum^{j\in\mathcal{J}_{its}} w_{js}},$$

and the total weight was

$$w_{its} = \sum_{j\in\mathcal{J}_{its}} w_{js},$$

for each cell, i, having spatial coordinates $\mathbf{s}_i$, within each year, t, and source, s.

1.2.5.5 Spatio-temporal modelling

Modelling was performed in the mgcv package for R (Wood 2011). We chose to use mgcv due to its fast and flexible model fitting and prediction methods, non-parametric regression terms, and the availability of the Beta likelihood. The mgcv package provides the functionality to include spatial random effects as a Markov Random Field for a defined neighbourhood structure, and this was used to account for spatial variation not attributable to the spatially varying covariates.

The proportion of coral cover, $\overline{\mathrm{y}}_{\mathrm{its}}$, at position $\mathrm{s_i}$, from source s, and time t was modelled using a generalised additive model (GAM), with the regression weights derived above, $\mathrm{w_{its}}$, used to adjust the contribution of each weighted mean to the likelihood. To aid in numerical stability, these weights were normalised prior to model fitting by dividing them by their mean value; hence the final regression weights had a mean of 1 and were $\mathrm{w'_{its}} = \frac{\mathrm{w_{its}}}{\overline{\mathrm{w}}}$. Thus, the weighted likelihood of the data, y, as a function of the parameters, θ, was:

$$L(\boldsymbol{y}|\boldsymbol{\theta}) = \prod^{i}\prod^{s}\prod^{t} w'_{its} p(\overline{y}_{its}|\boldsymbol{\theta}).$$

The Beta likelihood was parameterised in the mgcv package in terms of its mean, μ, and a common precision parameter, ϕ, for all i, t.

$$p(\overline{y}_{its}|\boldsymbol{\theta}) = \mathrm{Beta}(\mu_{it}, \phi).$$

These parameters are obtained from the more familiar shape parameters of the Beta distribution with the transformations $\mu_{it} = \frac{a_{it}}{a_{it}+b_{it}}, \phi_{it} = a_{it} + b_{it}$ and inverse transforms $a_{it} = \mu_{it}\phi, b_{it} = (1 - \mu_{it})\phi$. For a given value of μ, an increase in ϕ leads to a decrease in the variance of y (and hence an increase in precision). The parameterisation of the Beta in mgcv leads to a common value of ϕ for all i, t.

The logit of the mean parameter was a function of the covariates at location $\boldsymbol{s}_i$ and time t, denoted $\boldsymbol{x}_{it}^T$, $\boldsymbol{u}$ was a spatial random effect, and $\boldsymbol{\delta}$ was a temporal random effect, fit as a spline model for the year of observation,

$$\text{logit}(\mu_{it}) = \boldsymbol{x}_{it}^T\boldsymbol{\beta} + u_i + \delta_t.$$

The covariates with linear effects in the model, $\boldsymbol{x}_{it}^T\boldsymbol{\beta}$, included log(COTS) risk, no take zone, cyclone risk, sea surface temperature anomaly, light extinction, depth, distance to the nearest river mouth, reef shelf position, management zone, and an interaction between shelf position and management zone (Table 3).

The spatial random effect, which represented clusters of reefs, was defined using hierarchical clustering in the fastcluster package (Müllner 2013) to maximise the minimum geographic distance between points in adjacent clusters. This clustering provided a way to model spatial variation which may not be attributable to covariates, at a scale between individual reefs (for which only a small fraction are measured) and larger spatial groupings such as management zones and reef shelf. The spatial random effect is fit as a Markov random field with an adjacency matrix calculated with the fmesher tool from INLA (based on Hjelle and Dæhlen (2006)) that defines a neighbourhood structure using a mesh and considers nodes which are directly connected by the graph to be neighbours. The impact of weighting on the spatial model was such that clusters with higher total relative weights had smaller standard errors compared to a model where data were equally weighted. However, the weight does not affect neighbouring clusters; in other words, an increased weight in one cluster does cause shrinkage in low-weight neighbouring clusters.

The GAM described above was fit to all cells, years and sources to estimate the effects of covariates at the whole-of-the GBR scale, while adjusting for spatial and temporal trends. A backwards stepwise model selection procedure was used to sequentially remove non-significant covariates, until all of the covariates in the final model were significant at the α=0.05 level.

1.2.6 Predictions

Prediction locations were allocated to the centroids of the reference raster cells, which were spaced at regular 0.005 dd intervals, resulting in 85529 prediction locations. Covariates at each location and time were extracted from the raster layers and a weight of 1 was allocated to all prediction locations. The prediction locations were projected to the UTM coordinate system and the fitted model was used to generate predictions at each of the locations and times. The data source was accounted for in the model fitting through the weights, so there was no need to specify a survey data source for the predictions, $\hat{y}_{it}$.

Prediction was performed by simulating from the fitted model

$$p(\hat{y}_{it}|\widehat{\boldsymbol{\theta}}) = \mathrm{Beta}(\hat{\mu}_{it}, \hat{\phi}),$$

where $\mathrm{logit}(\hat{\mu}_{it})$ is the linear predictor described in section 1.2.4.5 and $\hat{\phi}$ is the precision parameter estimated during model fitting. For each cell and year in the prediction data frame 1000 samples were drawn and summarised with the mean, 10th and 90th quantiles, and standard deviations on the logit and response scales. We assessed the predictive ability of the model based on the coverage of 80% prediction intervals, the mean squared error (MSE), and the median absolute deviation (MAD) of the observed versus predicted values. These statistics were calculated both with and without the weighting scheme, to account for the relative importance of the observations in the model fitting. That is, observations with large weights were considered to contribute more to calculations of the MSE, MAD and 80% coverage.

The predicted coral-cover estimates, along with prediction standard deviations, were back-projected to a geographic coordinate system and converted to raster format for visualisation as map layers. A tile mapping service from the Geospatial Data Abstraction Library (GDAL 2016), was used to colour-map the output rasters and pass them to the GDAL2Tiles tool, which generated a collection of tiles for web-based visualisation within Cesium Globe. Predictions were not generated for cells where the centroid was at least 5m above sea level (i.e. land) or deeper than 50m below sea level (i.e. deeper than reef slope).

1.2.7 Model Assessment

We fit the model to two separate datasets to highlight differences in model predictions when a model is fit to data from multiple sources, as described above. First we fit the model to all of the data available (i.e. LTMP, MMP, Capricorn and Bunker, Heron, Catlin, and Reef Check) and used the methods described above to weight the data and then spatially aggregate it to the 0.005 dd scale.; we refer to as the “All data” model. Then we fit a model to the LTMP and MMP data only. Although we aggregated the data spatially to a 0.005 dd scale, we did not use a weighting scheme to account for differences in the data sources; we refer to this model as the “LTMP/MMP” model. We then focus on the Capricorn and Bunker group of reefs, including Heron Island, because it is an area where LTMP and MMP data are available along with numerous other data sources, which are not repeatedly measured on an annual or biennial basis. This allowed us to highlight differences in the model predictions within a region where LTMP and MMP routinely sample. More specifically, we compared the predictive ability of the models (MSE, MAD, and 80% coverage) when a model is fit to the LTMP and MMP data only, versus a model fit to all of the different sources of data.

1.3 Results

After spatially aggregating the data, there were 3451 coral cover estimates collected between 1992 and 2016. Covariate data were only available from 2002-2016, and so we excluded coral cover data collected prior to 2002. As a result, a total of 1753 observations were used in the coral cover model. The number of cells that contained coral cover data, for each source and year is shown in Figure 4. The LTMP and MMP provided a consistent long-term record of coral cover data, while the other datasets provided greater volumes of data in some cases, but only for individual years. Note that, data collection in 2016 occurred prior to that year's coral bleaching event.

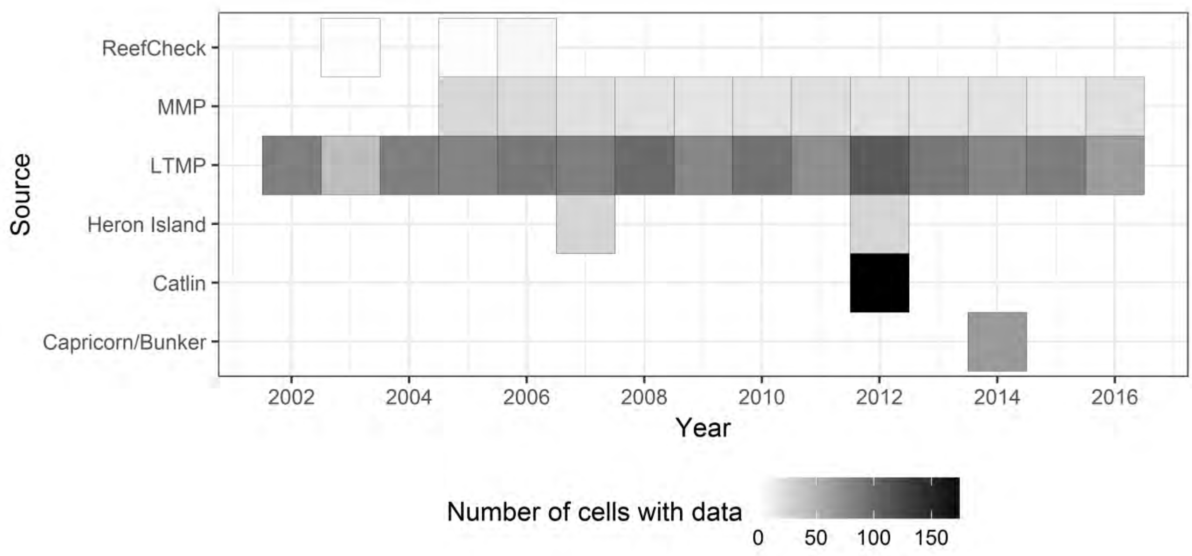


Figure 4 The number of reference raster cells containing at least one coral cover observation for each of the professional surveys and Reef Check citizen science data. Professional surveys included the Marine Monitoring Program (MMP), Long Term Monitoring Program (LTMP), the Heron Island and Capricorn and Bunker surveys, and the XL Catlin Seaview Survey.

1.3.1 Annotation of citizen science images

A total of 12 citizens annotated 218 Reef Check images, which is equivalent to 1758 whole-of-image annotations and 34969 individual point annotations. The average classification accuracy of citizens compared to the marine scientist was 0.8 (Figure 5). This suggests that the users who annotated the images were more often than not correctly identifying image features which were, and were not corals. The variability in the accuracy levels across the 20 images was relatively large, but consistent for the 12 users. This variability is likely attributed to image properties and the benthic composition; the 20 Catlin images used in the training set were selected to capture a wide variety of reef characteristics, such as haziness, sand, and soft and hard corals and these characteristics increased or decreased the users' ability to accurately classify coral. For example, the image with Media ID 5037 portrayed a sandy sea floor, which was easy for most users to classify correctly. In contrast, Media IDs 5029 and 5045 had the lowest classification accuracy rates and contained complex collections of hard and soft corals and, in the case of 5029, algae. Figure 6 shows the distribution of accuracy rates across each of the 218 Reef Check images which were annotated. The minimum image weight, w_{js}, was 7.69 (an image with two annotators), the mean was 69.99 and the maximum was 179.41 (an image with 11 annotators) (Figure 7).

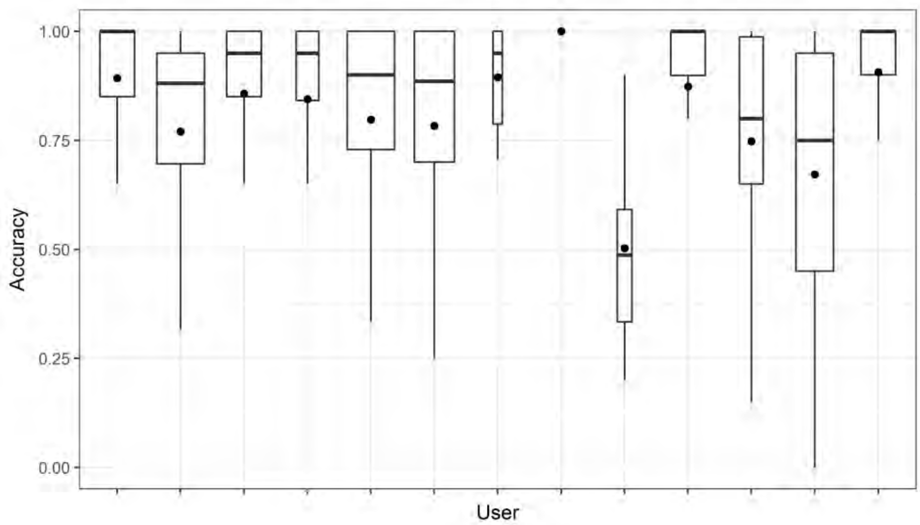


Figure 5 Accuracy of coral cover estimates obtained from Citizen Users compared to those of a marine scientist (whose accuracy is shown as 1). Black dots denote a user's mean accuracy across all images they annotated, and the width of the boxplot is proportional to the number of annotations performed.

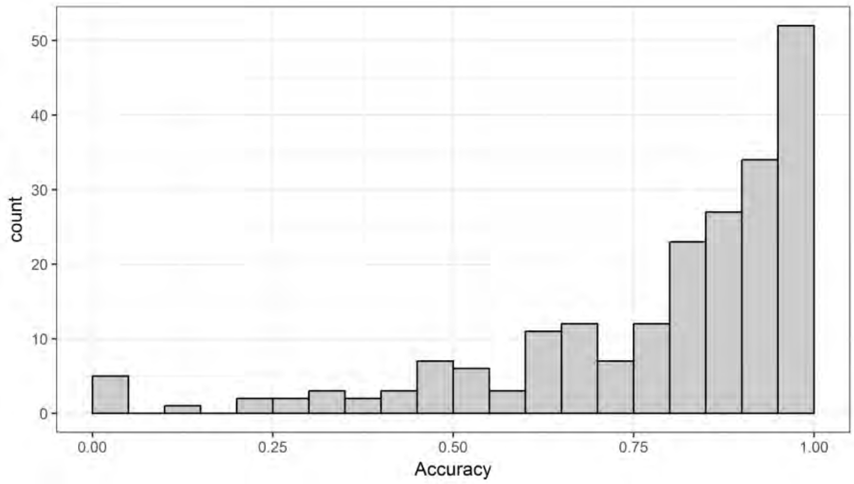


Figure 6 Overall classification accuracy for the Reef Check images that were annotated by citizens.

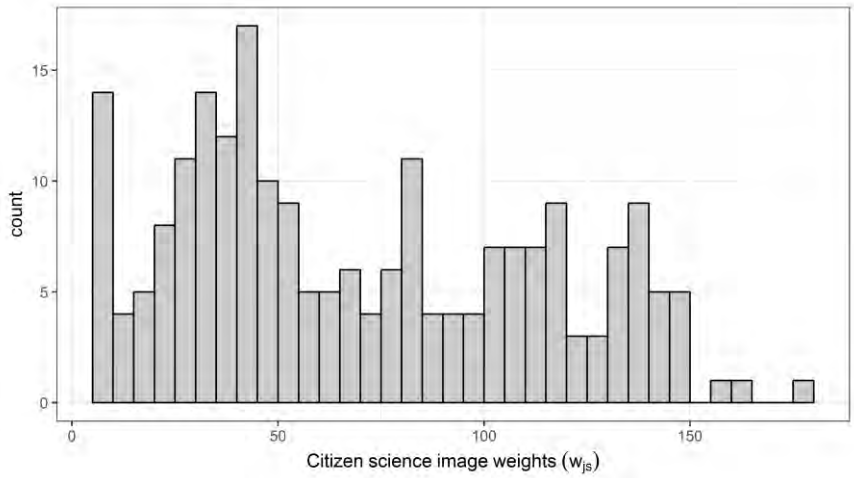


Figure 7 Weights allocated to each citizens-science image, computed from 12 participants' annotations of a collection of 218 images.

The Catlin, Heron Island, and Capricorn Bunker data sources had the largest weights per cell and year after aggregation and normalisation, due to the relatively large image extent, as well as the number of images and the number of annotation points to used estimate coral cover (Table 4, Figure 8). Reef Check images were allocated the smallest weights because there were only a small number of images (n=218), which also had an exceptionally small extent (Table 4).

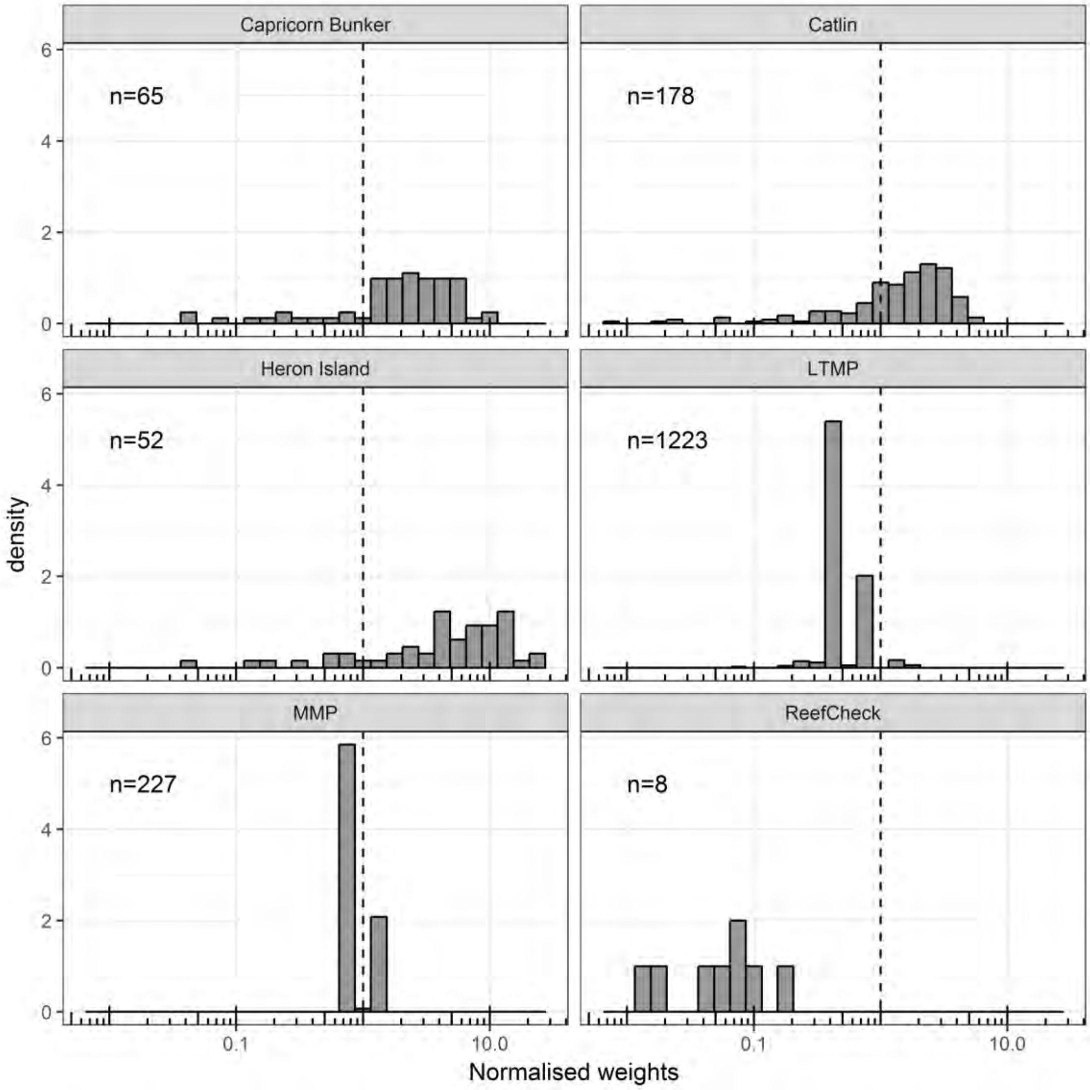


Figure 8 Normalised coral cover weights for each source and cell for coral cover estimates collected between 2002 and 2016. Sources include the Reef Check citizen-science data, Marine Monitoring Program (MMP), Long Term Monitoring Program (LTMP), Heron Island and Capricorn and Bunker surveys, and the XL Catlin Seaview Survey. The weights have been normalised (i.e. mean centred) and so they provide a relative measure of how influential each coral cover estimate is.

1.3.2 GBR scale coral cover model

The amount of data varied spatially and temporally, with particular regions of the reef only being monitored sporadically over time. This is not surprising because the LTMP and MMP are designed to provide consistent temporal coverage, at the expense of a wider spatial distribution. In contrast, surveys such as Catlin or Heron Island increase the overall spatial coverage of data, but their sampling is not longitudinal (Figure 4, Figure 9). Thus the number of cells containing coral cover estimates varied from year to year, even within surveys. The years with the largest total weight for the aggregated data occurred when at least one other survey was conducted in addition to the LTMP and MMP. For example, the Catlin survey was undertaken in 2012, which dramatically increased the spatial coverage of data, including in the Far North where no samples were previously collected. Thus, 2012 accounts for 35.2% of the total weight in the All data model due in part, to the large number of Catlin images (Figure 4). However, other surveys were conducted that year (Heron Island, LTMP, and MMP), which also contributed to the overall weight. This was also true when the Heron Island (2007) and Capricorn and Bunker group (2014) surveys were undertaken in addition to the LTMP and MMP. These years accounted for 12.0% and 13.9% of the total weight, respectively. For the other 12 years, the weight contributed by each year of data was between 1.3% and 4.2%.

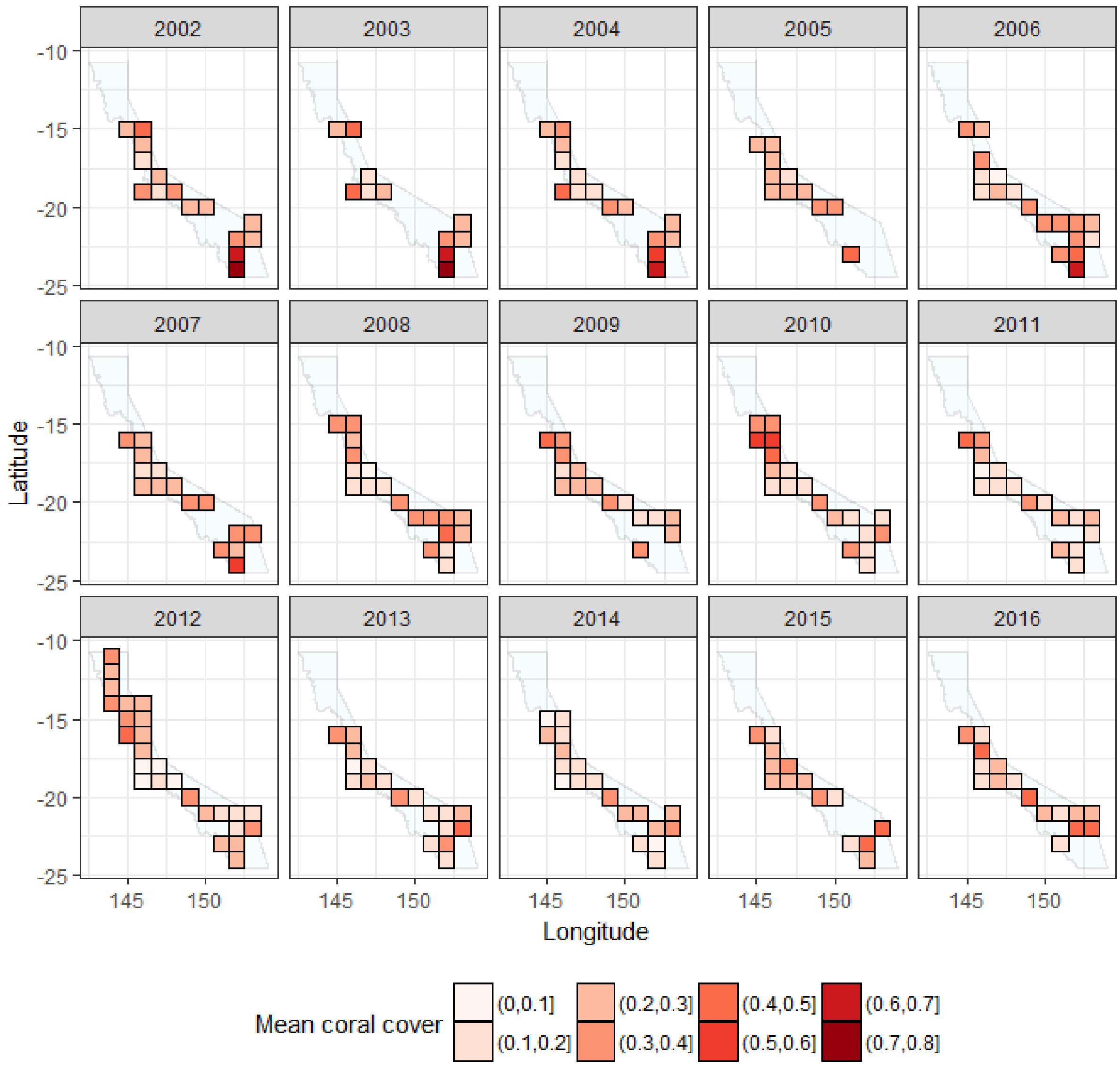


Figure 9 Weighted mean coral cover aggregated to a spatial scale of 1 square decimal degree (for visualisation purposes) for the years 2002-2016.

1.3.2.1 *Coral cover covariates*

The covariate effects in on coral cover in the All data model tended to reflect what we expected, given our conceptual model (Figure 2). Light extinction and the presence of a no take zone had a positive effect on coral cover (Table 5). After accounting for the positive effect of light, the depth had a negative effect on coral cover. Surprisingly, there tended to be less coral on the middle and outer shelves compared to the inner shelf (baseline case). However, this was after accounting for the spatial random effect and so some of the spatial variability was likely described by the reef clusters. For all of the other covariates, the confidence intervals of the parameters included zero, which suggests that they did not have a strong association with coral cover in this model. Thus, they were removed from the model.

Table 5 Parameter estimates and 95% confidence intervals for covariates in the spatio-temporal All data model of coral cover for the whole-of-the Great Barrier Reef (2002-2016).

Term	Estimate	2.5%	97.5%
Intercept	-1.578	-1.852	-1.304
No take zone	0.123	0.034	0.212
Light	0.362	0.195	0.529
Middle shelf	-0.509	-0.779	-0.239
Outer shelf	-0.434	-0.709	-0.16
Depth	-0.032	-0.039	-0.025

The spatio-temporal All data model accounted for changes in coral cover across the GBR in both space and time. Coral cover was predicted to be the highest (approximately 0.8) on the inner reefs near Bowen (between Mackay and Townsville) and lowest near Townsville (Figure 10). The predictions on outer reef shelves in this region had a relatively high level of prediction uncertainty (Figure 11), as very few reefs were sampled in this area. The logit-transformed standard deviations for the predictions were lowest in the Townsville/Whitsunday Management Zone, where the LTMP and MMP have sampled consistently since the programs' inception. Low coral cover was also predicted (with high certainty) in the Southern reaches of the GBR Marine Park, around the Capricorn and Bunker group, where cyclone risk is moderate and a large amount of data has been collected.

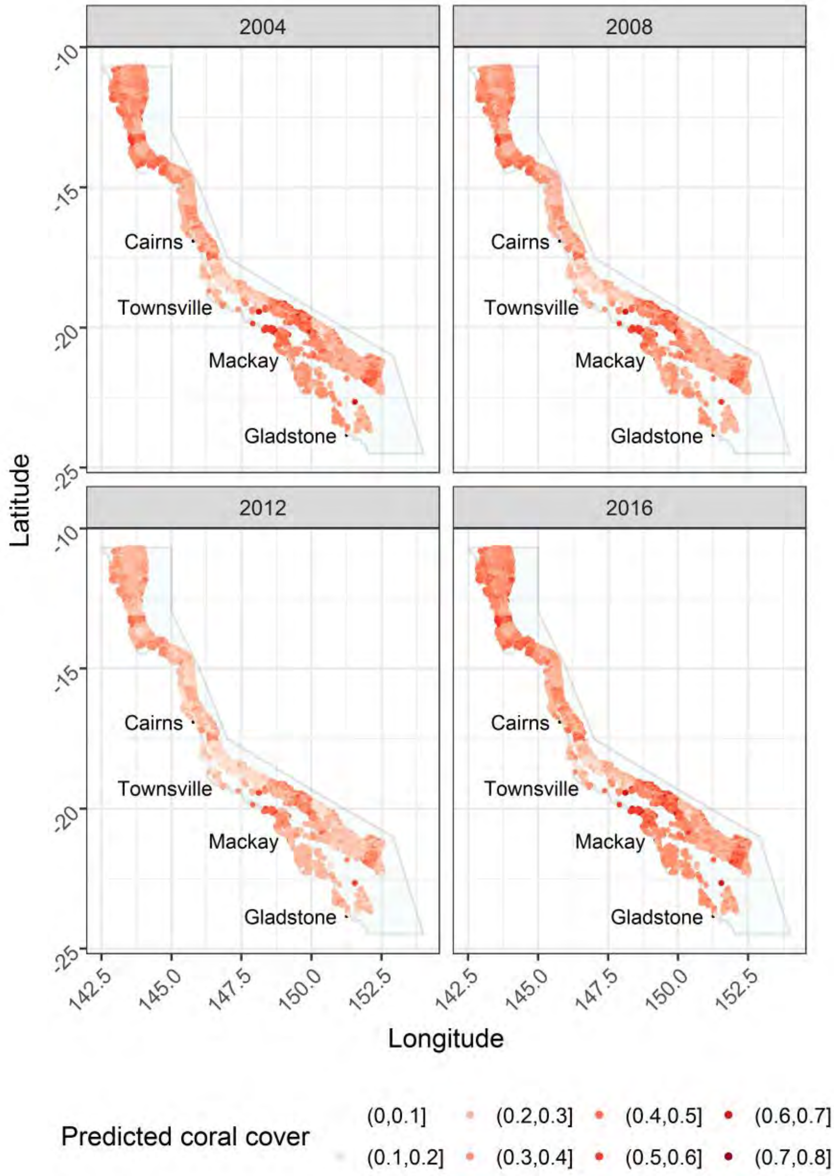


Figure 10 Predicted coral cover across the Great Barrier Reef Marine Park (blue polygon) for 2004, 2008, 2012 and 2016 using the All data model. Major coastal cities are shown as black dots.

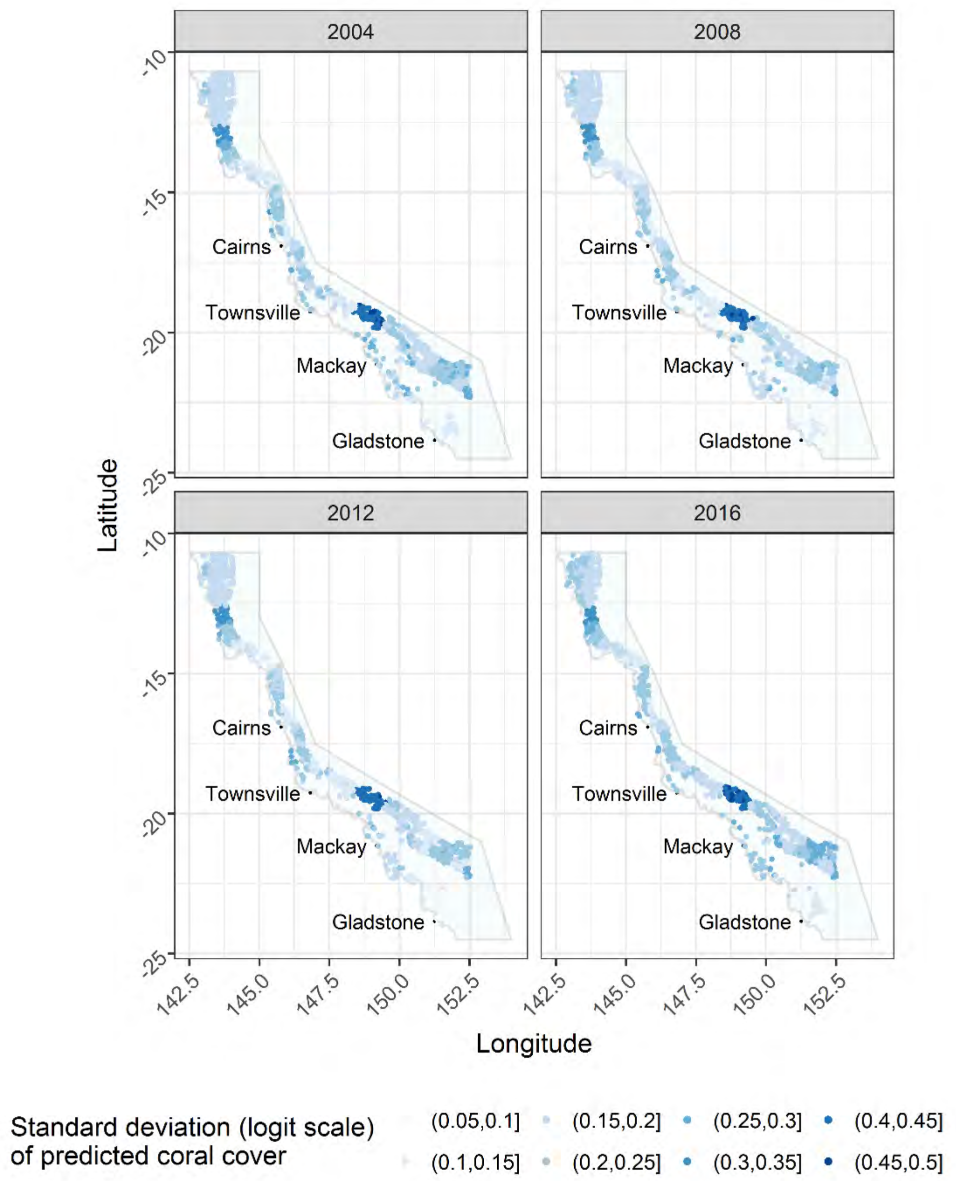


Figure 11 Prediction standard deviations, on the logit scale, for predicted coral cover across the Great Barrier Reef Marine Park (blue polygon) in 2004, 2008, 2012 and 2016 using the All data model. Major coastal cities are shown as black dots.

The addition or omission of additional coral cover data affected the temporal trend in the All data and the LTMP/MMP models (Figure 12). The temporal trend from 2002-2008 is similar in the two models, which is not surprising because the LTMP and MMP make up the majority of the data available prior to 2007. However, a major decrease in coral cover was observed between 2012 and 2014 in the All data model, followed by a sharp increase from 2014 to 2016 (Figure 12, left panel). In contrast, a much smaller decrease is observed in LTMP/MMP model from 2008-2012, followed by a steady increase from 2012-2016 (Figure 12, right panel). These decreases in the partial random effect correspond to cyclones Hamish (2009), Yasi (2011) and Ita (2013). Note that, coral cover estimates for 2016 were performed before the major coral bleaching event that was observed.

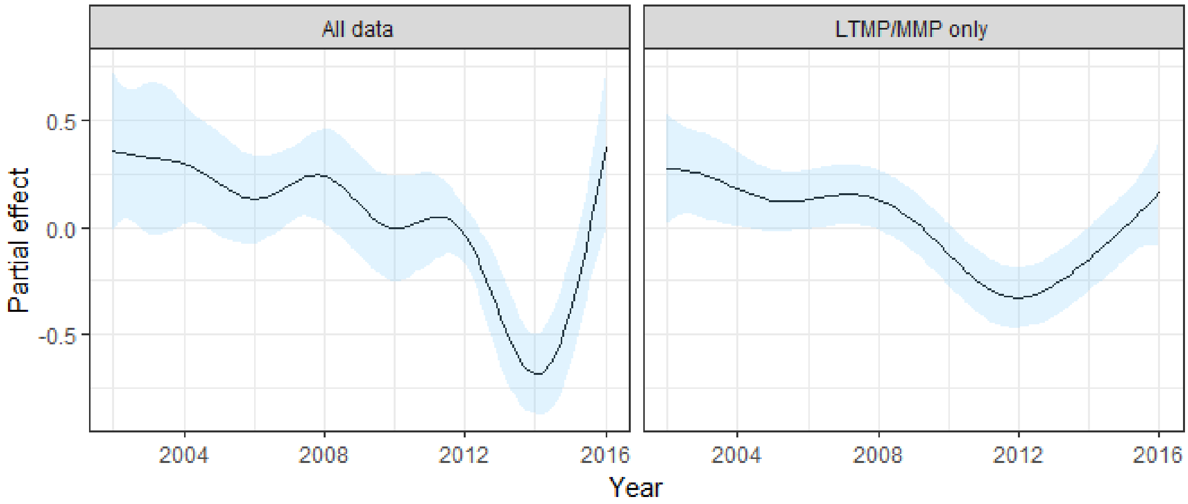


Figure 12 Partial effect of the temporal random effect on logit-transformed coral cover from the model fit to all the data (All data) and the model fit to the Long Term Monitoring Program an Marine Monitoring Program (LTMP/MMP only) model (2002-2016).

The weighted MSE for the All data model was 0.016 (unweighted MSE = 0.014) and the weighted MAD was 0.081 (unweighted MAD = 0.073), indicating that while the model did not capture all spatio-temporal variability, it was able to capture trends across the GBR (Table 6). The weighted 80% prediction interval coverage was 83.3% and the unweighted 80% coverage was 81.4%). Although this is slightly wider than anticipated, it does not suggest there is a problem such as overly confident predictions centred around a poorly estimated mean.

Table 6 Model diagnostics (unweighted and weighted) for predictions Great Barrier Reef from models using all the data available and only the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) data.

Model	**Coverage**	**80% Coverage Weighted**	**MSE**	**MSE Weighted**	**MAD**	**MAD Weighted**
All data	0.812	0.823	0.016	0.014	0.081	0.074
LTMP/MMP	0.802	0.740	0.015	0.018	0.075	0.088

1.3.3 Capricorn and Bunker Group

The coral cover predictions produced by the All data model were lower in the Capricorn and Bunker region than the predictions produced by the LTMP/MMP model (Figure 13). In addition, the logit-transformed standard deviations of the predictions for the All data model were approximately half that of those produced by the LTMP/MMP model, and there was more spatial variability in the uncertainty estimates (Figure 14). These results suggest that fitting the model to the full dataset provides greater certainty about the predicted values in these reefs, as well as finer-scale information about the spatial variability in those certainty estimates (Figure 14). Finally, model diagnostics for predictions made in the Southern Zone indicate that the All data model were more accurate and have better prediction coverage than the LTMP/MMP model (Table 7).

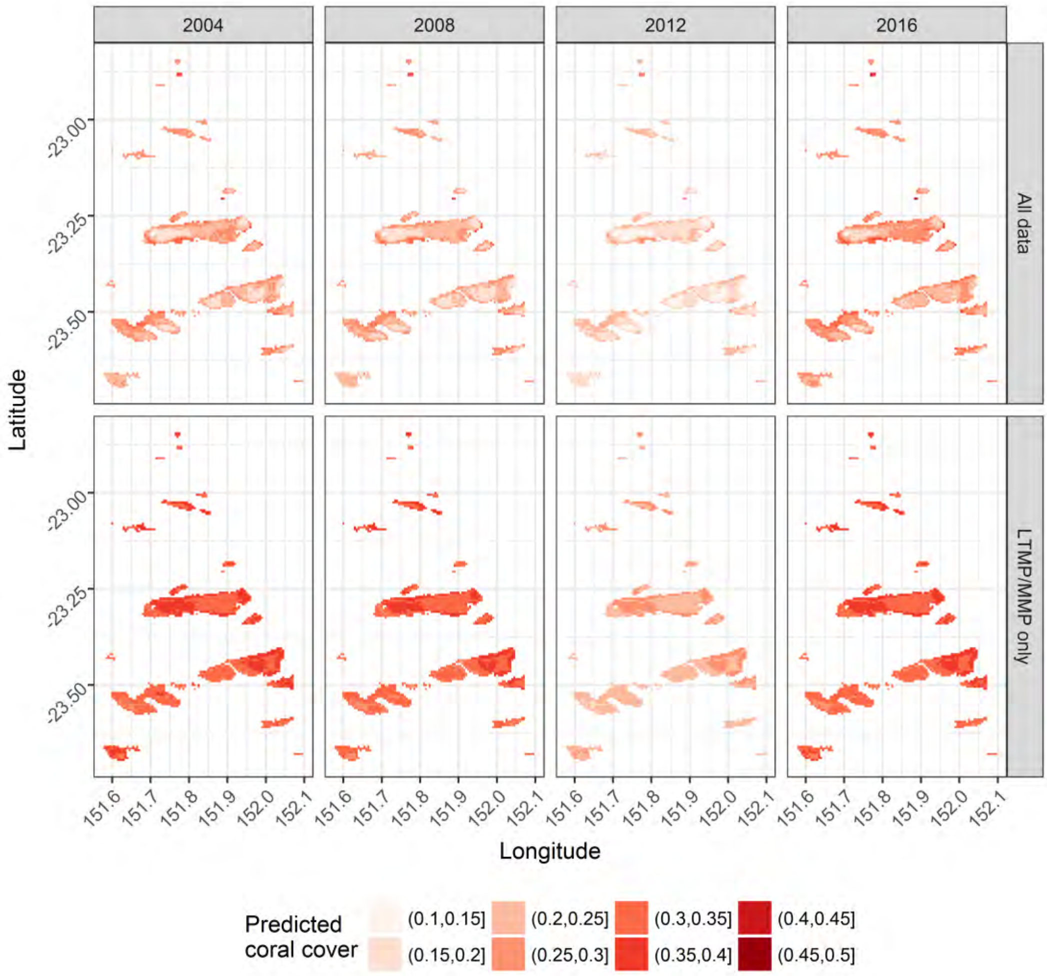


Figure 13 Predicted coral cover in the Capricorn and Bunker group of reefs from a model fit to all of the data sources (All data) versus another model fit to the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) data only.

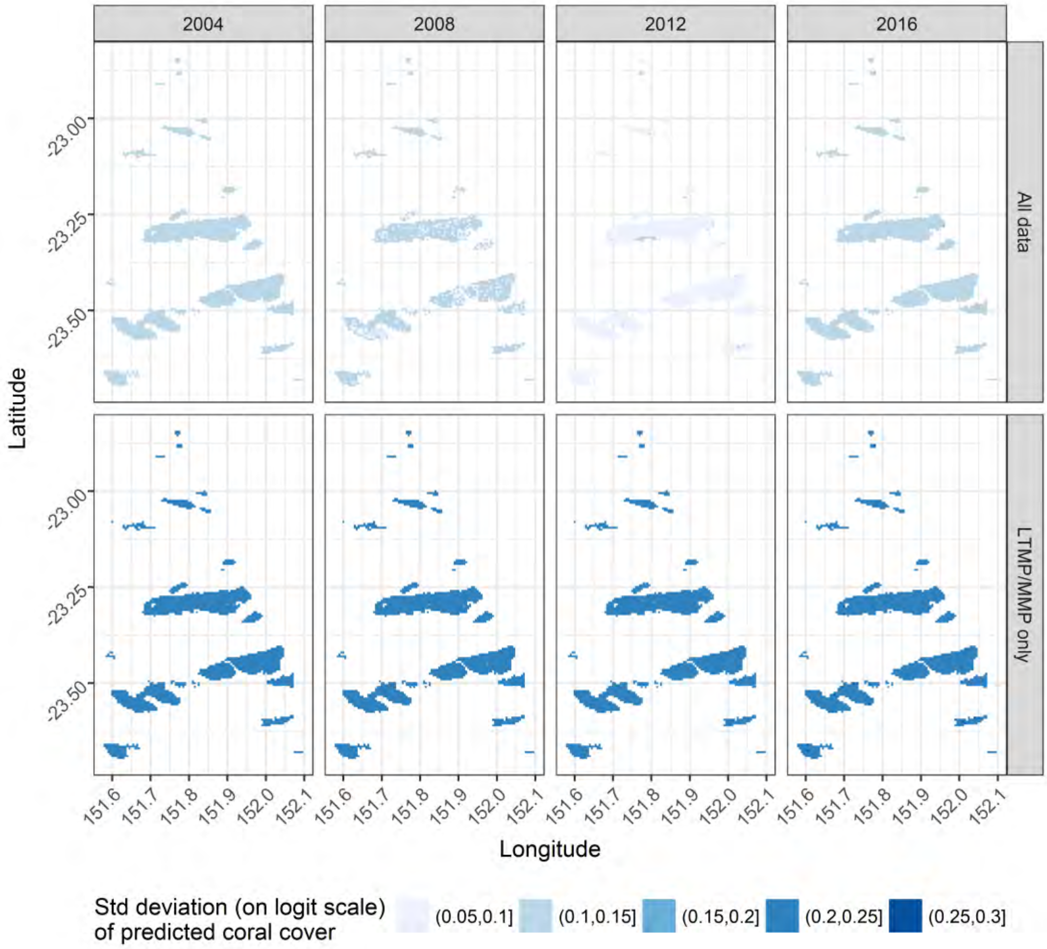


Figure 14 Prediction standard deviations (on the logit scale) of coral cover in the Capricorn and Bunker group of reefs from a model fit to all of the data sources (All data) versus another model fit to the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) data only.

Table 7 Model diagnostics (unweighted and weighted) for predictions in the Southern Management Zone of the Great Barrier Reef from a model fit to all of the data sources (All data) versus another model fit to the Long Term Monitoring Program and Marine Monitoring Program (LTMP/MMP) only.

Model	Coverage	Coverage Weighted	MSE	MSE Weighted	MAD	MAD Weighted
All data	0.681	0.736	0.024	0.016	0.095	0.078
LTMP/MMP only	0.613	0.549	0.026	0.029	0.112	0.122

1.4 Discussion

1.4.1 Data synthesis

In this study, we demonstrated how data from multiple sources, such as professional monitoring and citizen science data, can be combined within a single statistical model and used to make predictions, with estimates of uncertainty, throughout the GBR and over time. We achieved this by implementing a mechanistically based weighting scheme that accounts for the differences in survey design and coral-cover estimation method, as well as the inherent quality of the images (Table 4). We used coral cover as an example, but this general approach is equally viable for other variables collected in the marine environment, as well as in other ecosystems.

The modelling framework we developed provides a way to integrate coral cover estimates derived from citizen-contributed images and citizen annotations of hundreds of images, while still accounting for differences in the quality of citizen science data compared to professional survey data. As a result, more data are available to fit the model of coral cover, which results in an overall increase in information about coral cover throughout the GBR. In this particular case, the model results suggest that including data sourced from surveys other than longitudinal ones (e.g. Catlin, Heron Island, Reef Check and Capricorn Bunker), in addition to the LTMP and MMP, resulted in a 22.2% reduction in uncertainty based on the weighted MSE. Nevertheless, the effect of incorporating additional data on the model's predictive accuracy will vary spatially and temporally depending on the density of existing data nearby (in space and time), as well as the source and quality of the new data being integrated.

1.4.2 Model results

The relationships between coral cover and the covariates in the model tend to reflect what we expected based on our ecological understanding of coral cover. For example, Mellin and others (2016) analyzed 20 years of data from the GBR and found that the magnitude of disturbances within no-take zones were significantly lower than neighboring unprotected areas, and that when disturbances did occur, corals were able to recover more quickly. Less coral cover is typically expected with depth (Logan and Tomascik 1991); however this relationship may be complicated because corals situated at deeper locations may be less disturbed by cyclones (Harmelin-Vivien 1994). The positive relationship between light attenuation (i.e. penetration) and coral cover may be the result of a symbiotic relationship between corals with algae, which increases levels of photosynthesis at deeper locations and provides more energy for corals to grow (Hoegh-Guldberg 1999). However, the relationship between coral cover and light exposure is not always positive. Reef locations receiving more light are exposed to more solar irradiance, which may increase the vulnerability of coral to bleaching events (Anthony et al. 2011).

Not surprisingly, the temporally static covariates we used to represent these dynamic processes (Table 3) were not significant in our model (Table 5). Although many of these covariates are expected to change over time (e.g. COTS and cyclone risk), the covariate rasters were only available as long-term averages. We believe that the predictive ability of the model could be significantly improved by including spatio-temporal covariates that represent disturbances such as COTS outbreaks, coral bleaching, and cyclone impacts, as well as temporally dynamic chlorophyll and secchi depth data. In addition, the cumulative effect of disturbances has also been shown to undermine coral resilience on the GBR (Vercelloni et al. 2017) and it may be possible to capture differences in coral recovery rates in a spatio-temporal statistical model. At present, temporally dynamic layers of disturbances such as COTS, cyclones, disease outbreak, and bleaching are not available, but these layers are currently under development (Pers. Comm., C. Mellin). The inclusion of these data in the model should increase our ability to predict temporal variations in coral cover resulting from disturbances.

The temporal term was able to describe some changes in coral cover over time (Figure 12), which were not captured by the model covariates. As we mentioned previously, decreases in the partial effect for the temporal trend in the All data model occurred roughly one year after cyclones Hamish (2009) and Ita (2013). In contrast, the LTMP/MMP model does not appear to capture the effects of these two cyclones; although it does show a decrease in 2012, which was one year after cyclone Yasi (2011). Thus, adding additional data to the model appears to help capture temporal trends in the data, even when those data have not been collected over time. Ideally, a spatio-temporal random effect would be used to describe the effects of disturbances, which affect different portions of the reef, rather than separate spatial and temporal random effects. We attempted to include this term in the model, but there was not enough data to estimate it. However, as more data becomes available, it may be possible to include a fully coupled spatio-temporal random effect in the model.

1.4.3 Citizen science data

Citizen science data currently has little weight in the model compared to the professional survey data because of the small number of Reef Check images, the relatively small extent compared to the professional monitoring images, and the small number of annotators. However additional elicitation of images will increase the weight allocated to these estimates and will also increase the spatio-temporal coverage of coral cover data within the GBR. We extracted approximately 900 images from the Reef Check MiniDV tapes, but it was logistically infeasible for the team and Reef Check volunteers to annotate all of the images. As such, the 218 images included in this study represent only 24% of the 900 extracted images and these 900 images represent only 10% of the available video surveys undertaken by Reef Check between October 2002 and April 2009. Additional images contributed by recreational divers and other citizen science groups would also dramatically increase the number of images available for elicitation, which in turn would increase the weight attributed to citizen-contributed data in the model.

1.4.3.1 Image quality

We expect citizen science images to have variable quality due to camera characteristics and user ability. Although we did not attempt to assess image haziness in this study, there are a number of ways it could be accomplished. Image blur could be assessed with the no-reference perceptual blur metric (Crété-Roffet et al. 2007) which calculates a score, $\mathrm{blur_F}$, between 0 (sharp) and 1 (completely blurred). This is achieved by comparing the pixel intensity of the original image and versions of the image which have been blurred in the vertical and horizontal directions. The multiplicative sub-weight used in the citizen and professional monitoring weighting schemes described here would therefore be $\mathrm{w_{b_j}} = 1 - \mathrm{blur_F}$. A less technical alternative would be to ask citizens eliciting images to score the image clarity, or blurriness, and these aggregated scores could be rescaled between 0 and 1 and used as $\mathrm{w_{b_j}}$.

All of the images included in the coral cover model were also assigned an orientation weight of $\mathrm{w_{o_{js}}} = 1$ because they were oriented straight down towards the sea bed, perpendicular to the water surface. However, this may not be true of citizen contributed images. As such, an orientation weight could be derived by estimating the proportion of the image that does not include water. This proportion could be obtained by thresholding blue values in the image, identifying a contiguous block of blue, and calculating the complement of the area as a fraction of the image area. Alternatively, these proportions could also be elicited by citizens during the elicitation process.

1.4.3.2 Accuracy

Citizen scientists' accuracy in distinguishing coral from other reef features may change over time as their ability to detect hard corals improves. As such, a user’s accuracy weight should be regularly re-evaluated. One way to achieve this would be to have citizen scientists periodically annotate images that have been annotated by experts. The user's accuracy score could be displayed after re-evaluation to encourage citizens to re-read the training document if necessary. Gamification of the annotation process could also increase competition between citizen elicitors and achievement badges could be awarded for performing a given number of annotations (e.g. 10, 50, 100, and 1000), having a particular accuracy rate, improving their accuracy rate, being the first to annotate a particular reef, and/or having the most annotations in a particular region of the reef. In the future, the training document could also be extended to a training module within the 2D or 360-degree elicitation tools, giving users the ability to annotate a set of images previously annotated by expert marine scientists. This could be used to provide instant feedback on whether citizens have correctly identified coral and non-coral features in the images.

1.4.4 Management implications

Exploratory analysis of the aggregated data may already permit some interpretation of spatio-temporal trends (e.g. Figure 12). However, the advantage of a spatio-temporal model is that it provides a way to make predictions, with estimates of uncertainty, in locations where coral cover was not observed. This provides a holistic snapshot of coral cover condition across the GBR, based on the best available data. The estimates of prediction uncertainty also provide a great deal of information for management. At the most basic level, differences in prediction uncertainty help managers understand where they can be most confident, or should be least confident in the predictions. This information could be used to prioritise management actions, or identify areas where additional information is needed before management actions are implemented. Prediction uncertainty can also be used to guide future sampling efforts within and between organisations. In areas where the number of measurements is currently high, additional samples may not significantly impact the accuracy or the precision of the predictions. However, additional samples in areas where there are few or no observations can drastically change the model predictions and reduce the estimates of uncertainty. These estimates of uncertainty can then be shared between organisations, so that sampling across the expanse of the GBR is better coordinated, regardless of whether those collecting the data are professional monitoring teams or citizen scientists.

1.5 References

Anthony, K., Maynard, J.A., Diaz-Pulido, G., Mumby, P.J., Marshall, P.A., Cao, L., and Hoegh-Guldberg, O. (2011) ‘Ocean acidification and warming will lower coral reef resilience’. *Global Change Biology*, 17(5):1798-1808.

Beaman, R.J. (2010) *Project 3DGBR: a high-resolution depth model for the Great Barrier Reef and Coral Sea.* Marine and tropical sciences research facility (MTSRF) project 2.5i.1a Final Report. Reef and Rainforest Research Centre, Cairns, Australia. Available at: https://www.deepreef.org/images/stories/publications/reports/Project3DGBRFinal_RRRC2010.pdf

Beijbom, O., Edmunds, P. J., Roelfsema, C., Smith, J. and others (2015) 'Towards automated annotation of benthic survey images: Variability of human experts and operational modes of automation', *PLOS ONE*. Public Library of Science, 10(7), pp. 1–22. doi: 10.1371/journal.pone.0130312.

Bivand, R. and Lewin-Koh, N. (2016) *maptools: Tools for reading and handling spatial objects*. Available at: https://CRAN.R-project.org/package=maptools.

Bivand, R. and Rundel, C. (2016) *Rgeos: Interface to geometry engine - open source (geos)*. Available at: https://CRAN.R-project.org/package=rgeos.

BOM (2014) *eReefs marine water quality dashboard data product specification*. Bureau of Meteorology. Available at: http://www.bom.gov.au/environment/activities/mwqd/documents/data-product-specification.pdf.

ACrété-Roffet, F., Dolmiere, T., Ladret, P. and Nicolas, M. (2007) 'The Blur Effect: Perception and Estimation with a New No-Reference Perceptual Blur Metric', in *SPIE Electronic Imaging Symposium Conf Human Vision and Electronic Imaging*. San Jose, United States, pp. EI 6492–16. Available at: https://hal.archives-ouvertes.fr/hal-00232709.

Dana, P. (2008) 'Encyclopedia of geographic information science', in Kemp, K. K. (ed.). Thousand Oaks, CA: SAGE Publications Ltd, pp. 349–351.

De'ath, G. (2007) *The spatial, temporal and structural composition of water quality of the Great Barrier Reef, and indicators of water quality and mapping risk*. Unpublished report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns, Australia. 71pp.

ESRI (2016) *ArcGIS Desktop: Release 10.3.1*. Redlands, CA: Environmental Systems Research Institute.

GBRMPA (2014) 'Great Barrier Reef Marine Park Authority GeoPortal'. Great Barrier Reef Marine Park Authority. http://www.gbrmpa.gov.au/geoportal/.

GDAL (2016) *GDAL - geospatial data abstraction library*. Version 2.1.2. Open Source Geospatial Foundation. Available at: http://gdal.osgeo.org.

Gonzalez-Rivero, M., Bongaerts, P., Beijbom, O., Pizarro, O., Friedman, A., Rodriguez-Ramirez, A., Upcroft, B., Laffoley, D., Kline, D., Bailhache, C., Vevers, R. and Hoegh-Guldberg, O. (2014) 'The Catlin Seaview Survey - kilometre-scale seascape assessment, and monitoring of coral reef ecosystems', *Aquatic Conservation: Marine and Freshwater Ecosystems*, 24(S2), pp. 184–198. doi: 10.1002/aqc.2505.

Harmelin-Vivien, M.L. (1994) 'The effects of storms and cyclones on coral reefs: A review'. Journal of Coastal Research, Special Issue 12: Coastal Hazards: 211-231.

Hijmans, R. J. (2016) *Raster: Geographic data analysis and modeling*. Available at: https://CRAN.R-project.org/package=raster.

Hoegh-Guldberg, O. (1999) 'Climate change, coral bleaching and the future of the world's coral reefs'. Marine and Freshwater Research, 50: 839-866.

IMOS (2015) *Wave time-series*. Australian National Mooring Network. Accessed 11/05/17. http://data.aodn.org.au/IMOS/ANMN/QLD/GBRHIS/Wave/IMOS_ANMN-QLD_ETWZ_20120925T060600Z_GBRHIS_FV01_GBRHIS-1209-AWAC-11_END-20130323T010300Z_C-20130606T034142Z.nc

Joint Nature Conservation Committee (2012) *EMODnet Seabed Habitats (EUSeaMap) Project - Technical Appendix No. 1*. UK Government. 29 pages. Available at: http://www.emodnet-seabedhabitats.eu/pdf/TechnicalAppendix_Light_EUSeaMap_20120808_final2.pdf

Jonker, M., Johns, K. and Osborne, O. (2008) *Surveys of benthic reef communities using underwater digital photography and counts of juvenile corals*. Standard Operating Procedure 10. Australian Institute of Marine Science.

Logan, A., and Tomascik, T. (1991) 'Extension growth rates in two coral species from high-latitude reefs of Bermuda'. Coral Reefs, 10: 155-160.

Mellin, C., MacNeil, M.A., Cheal, A.J., Emslie, M.J., and Caley, M.J. (2016) 'Marine protected areas increase resilience among coral communities'. *Ecology Letters*, 19: 629-637.

Müllner, Daniel. 2013. 'fastcluster: Fast Hierarchical, Agglomerative Clustering Routines for R and Python.' *Journal of Statistical Software,* 53(9):1-18. doi: 10.18637/jss.v053.i09.

Pebesma, E. J. and Bivand, R. S. (2005) 'Classes and methods for spatial data in R', *R News*, 5(2), pp. 9–13. Available at: http://CRAN.R-project.org/doc/Rnews/.

R Core Team (2016) *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www.R-project.org/.

Roelfsema, C.M. (2012) 'Benthic and substrate cover data derived from photo-transect surveys in Heron Reef'. PANGAEA. doi: 10.1594/PANGAEA.790775.

Sammut, C. and Webb, G. I. (eds) (2010) *Encyclopedia of machine learning*. Boston, MA: Springer US, pp. 9–10. doi: 10.1007/978-0-387-30164-8_3.

Sweatman, H., Burgess, S., Cheal, A., Coleman, G., Delean, S., Emslie, M., McDonald, A., Miller, I., Osborne, K. and Thompson, A. (2005) *Long-term monitoring of the Great Barrier Reef*. Status Report 7. Townsville, Qld, Australia: Australian Institute of Marine Science.

Vercelloni, J., Caley, MJ., Mengersen K. (2017) 'Crown-of-Thorns starfish undermine the resilience of coral populations on the Great Barrier Reef'. *Global Ecology and Biogeography*, DOI: 10.1111/geb.12590.

Wolff, N. H., Wong, A., Vitolo, R., Stolberg, K., Anthony, K. R. N. and Mumby, P. J. (2016) 'Temporal clustering of tropical cyclones on the great barrier reef and its ecological importance', *Coral Reefs*, 35(2), pp. 613–623. doi: 10.1007/s00338-016-1400-9.

Wood, S.N. (2011) 'Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models'. *Journal of the Royal Statistical Society (B),* 73(1):3-36.

2. Reef Aesthetics experiment






2.1 Introduction

The Great Barrier Reef (GBR) was listed as World Heritage Area in 1981 and is widely recognized for *containing superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance* (Criterion vii, Johnston, Smith, and Dyke 2013). That is, under the World Heritage Convention, the Australian federal and Queensland state governments have a responsibility to monitor and report on the GBR aesthetic values, as well as more traditional ecosystem-health measures such as water quality and biological diversity. A large number of visual criteria have been evaluated as part of the GBR aesthetic-value assessment in an effort to identify attributes that embody the values described in Criterion vii. However, previous studies have shown that this methodology cannot be used to capture non-visual criteria and as a result, other sensory senses that are potentially stimulated during immersive experiences within the underwater world are not considered in the assessment of the GBR aesthetic values (Lucas et al. 1997, Pocock 2002, Johnston, Smith, and Dyke 2013).

In the Reef Aesthetics experiment, a virtual reality (VR) elicitation tool was used to interview three groups of people with different links and experiences with coral reefs: 1) the Marine Scientist group, which consisted of reef experts with strong links to the GBR; 2) the Experienced Diver group, who have experienced the underwater environment; and 3) a Citizen group, where participants have only seen the GBR through documentaries and images. Our goal was to gain knowledge about people's perception of beauty to help managers and conservationists better assess reef aesthetic value.

2.2 The experiment

2.2.1 Survey questions

We selected a set of visual underwater indicators, which were chosen based on key factors adopted to assess GBR aesthetic value (Johnston, Smith, and Dyke 2013). Below the water, reef aesthetic values are typically described by water clarity, the variety of shapes and forms of corals, shells and fish, marine life abundance, diverse colours and an additional "wow" factor such as the presence of large marine creatures (i.e. sharks, turtles, dugongs, whales, etc.). We used this knowledge to prepare 9 questions with Yes and No answers in a non-technical language so that they would be comprehensible by all three groups. The questions were:

Q1. Do you find the image visually pleasant?

Q2. Is the image hazy?

Q3. Do the live corals on the reef form structurally complex habitats?

Q4. Do you see evidence of damage to the reef?

Q5. Is the reef mostly one colour?

Q6. Can you see individual fish?

Q7. Can you see schools of fish?

Q8. Can you see more than one type of fish?

Q9. Do you see any organisms other than corals or fish?

For each of the 9 questions, the participant was also asked about the certainty associated with their answer (i.e. very sure, sure, and not sure).

2.2.2 Survey participants

Elicitations were performed by 4 interviewers at several locations in Queensland from the end of September to mid-November 2016. For the most part, Marine Scientists were interviewed at the Australian Institute of Marine Science, the GBR Marine Park Authority and the University of Queensland (UQ) Global Change Institute. Participants in the Experienced Divers group were members of the UQ scuba-diving club “Unidive”, while Citizens were interviewed as part of the ReefBlitz event in Brisbane and at QUT.

2.2.3 The training document

Prior to elicitation, participants in the reef aesthetics experiment were provided with a training document. The training document explained 1) the experiment, 2) the questions that participants would be asked and the criteria for answering them, and 3) the uncertainty grades attached to each response. Its purpose was to provide a summary of the experiment in a consistent manner for all participants.

Each participant was asked nine Yes-or-No questions in the VR interface, which were previewed in the training document. The definitions for concepts and question scope in the training document were designed to help the participant respond adequately to each question. In particular, the following were defined:

- Desirability
- Haziness
- Structural complexity

- Damage types
- Colours
- Individual fish and schools of fish
- Organisms other than corals or fish

Desirability was defined as a personal appraisal of the participants regarding the beauty of the landscape that they were immersed in. The concept of haziness was defined as being unable to see clear outlines of the different objects in the distance. Figure 15 was used as example to showcase a hazy landscape.

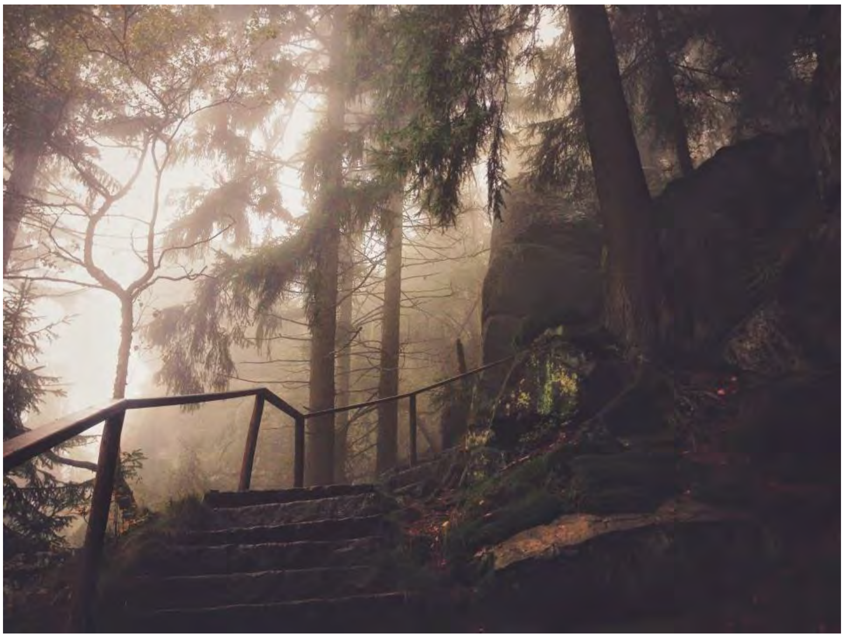


Figure 15 Example of a hazy landscape where tree boundaries in the background are not discernible.

Structural complexity was not rigidly defined; instead, participants were asked to view the reef from the perspective of a small fish. They were told that, if, as a small fish, they could find many places to hide in the reef, the reef should be considered a complex habitat. Participants were also asked to distinguish between topography and structural complexity; in other words, terrain with varied topographical features, such as hills, was not necessarily complex (Figure 16).

(a)

(b)

Figure 16 Examples of (a) a complex habitat and a (b) non-complex habitat.

Different types of damage (e.g. coral bleaching/disease, storm damage, fish predation, and pollution) were explained using images (Figures 17-21). Participants were also encouraged to describe other damage, even if those types of damage were not explained in the training document.

Figure 17 Example of recent coral bleaching. Image courtesy of Great Barrier Reef Marine Park Authority (GBRMPA).

Figure 18 Coral landscape after a coral bleaching event. Image courtesy of the XL Catlin Seaview Survey.

Figure 19 Coral reef before and after tropical cyclone Ita. Image courtesy of the XL Catlin Seaview Survey.

Figure 20 Signs of fish predation resulting in broken corals. Image courtesy of the Long Term Monitoring Program, Australian Institute of Marine Science

Figure 21 Macro-algae on a coral reef related to land-based pollution. Image from (DeGeorges, Goreau, and Reilly 2010).

The notion of colour intensity and diversity was addressed by asking about a lack of many colours within an image. Individual fish were defined as fish that could easily be counted one-by-one, and fish were said to be schooling if there was a group of similar looking fish and it would not be possible to provide that count. For the study, corals were defined as hard corals, since the focus was on reef-building organisms and soft corals do not build reefs. Therefore, questions relating to other organisms included soft corals. Further examples of other organisms given to the participant were sea cucumbers, turtles, algae and sponges.

2.2.4 The training image

Each participant was shown five 360-degree images inside a Samsung GearVR headset, including one training image provided by the XL Catlin Seaview Survey (Figure 22). The training image was the same for all participants and was used to help standardise subsequent responses. Participants were asked to base their impression of all subsequent images on their judgements about the training image, which represented a medium-quality reef typical of the GBR.

Figure 22 The training image (equirectangular projection), taken at Reef 13040 (143.9601°E, 13.25687°S). The large grey triangle is the diver, who has been removed from the image for privacy reasons. Copyright XL Catlin Seaview survey, see 360-images here: http://globalreefrecord.org/transect_explorer/15019/image/150190084/threesixty

2.2.5 Other images

After viewing the training image, the participants were shown four images from a pool of 38 images provided by the XL Catlin Seaview Survey. The images were selected using an experimental design that ensured that each participant was shown a subset of images that captured the variability in visual attributes within the 39 images, and each image was elicited approximately the same number of times. The images represented a range of attributes hypothesized to describe aesthetic value within the GBR. These included the coral cover and structural complexity, coral health, colour range, damage to corals, fish abundance and diversity, as well as visibility.

2.2.5.1 *Image clustering*

As part of the sampling design, hierarchical clustering analysis was performed on the images. Firstly, the features in each of the 39 images were rated by the team (Table 8). An agglomerative clustering algorithm was then used to group the images into three categories based on their features using a dissimilarity matrix (Figure 23). The clustering was implemented using the cluster package (Maechler et al. 2016) in R statistical software (R Core Team 2016).

Table 8 Image attributes and the levels of the attribute that were considered in the hierarchical clustering algorithm.

Attributes	Levels
Colour range	High, Medium, Low
Coral cover	High, Medium, Low
Coral health	Good, Medium, Poor
Coral presence	Yes, No
Damage to corals	Yes, No
Fish diversity	Yes, No
Habitat complexity	High, Medium, Low
Schools of fish present	Yes, No
Visibility	High, Medium, Low

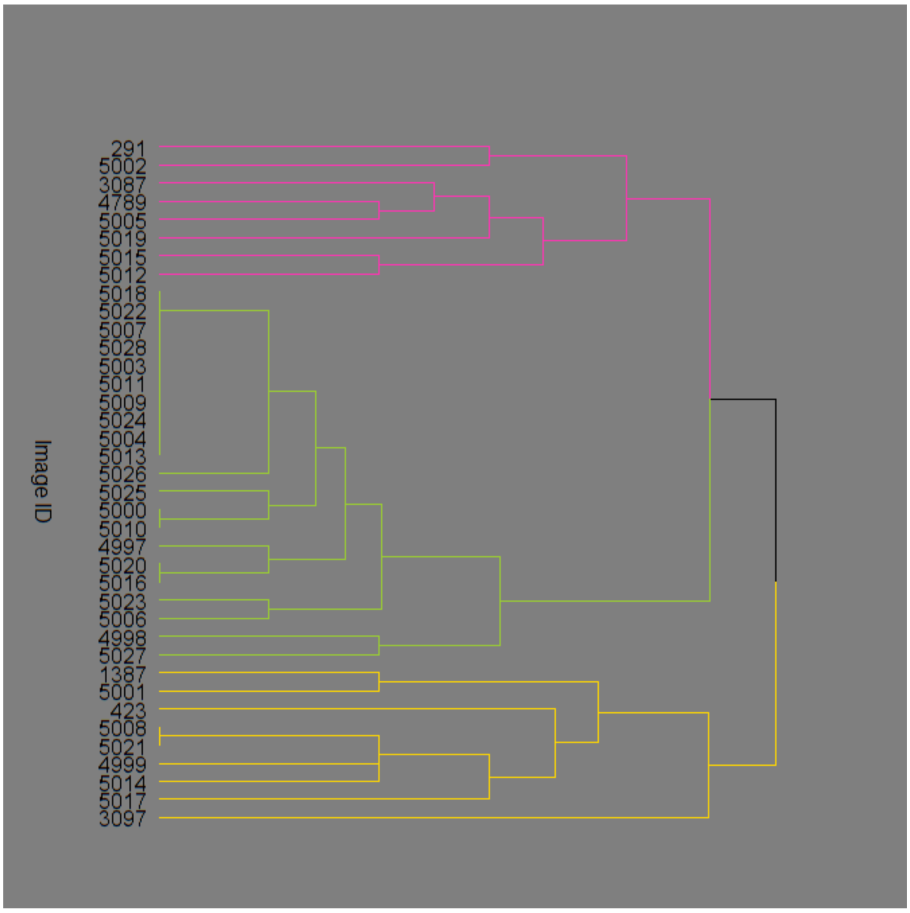


Figure 23 Dendrogram from the hierarchical clustering analysis. Groups are coloured differently; magenta is Cluster 1, gold is Cluster 2, and green is Cluster 3.

Cluster 1 was characterised by damaged corals, with poor to medium coral health, and moderate coral cover, but high habitat complexity (Figure 24). Cluster 2 contained images from the most degraded sites and was characterised by low to medium structural complexity, poor to medium visibility, and low coral cover with generally poor coral health. Images in cluster 3 were characterised by their diversity of colour, abundant fish life, high coral health and coral cover, and a generally pristine environment.

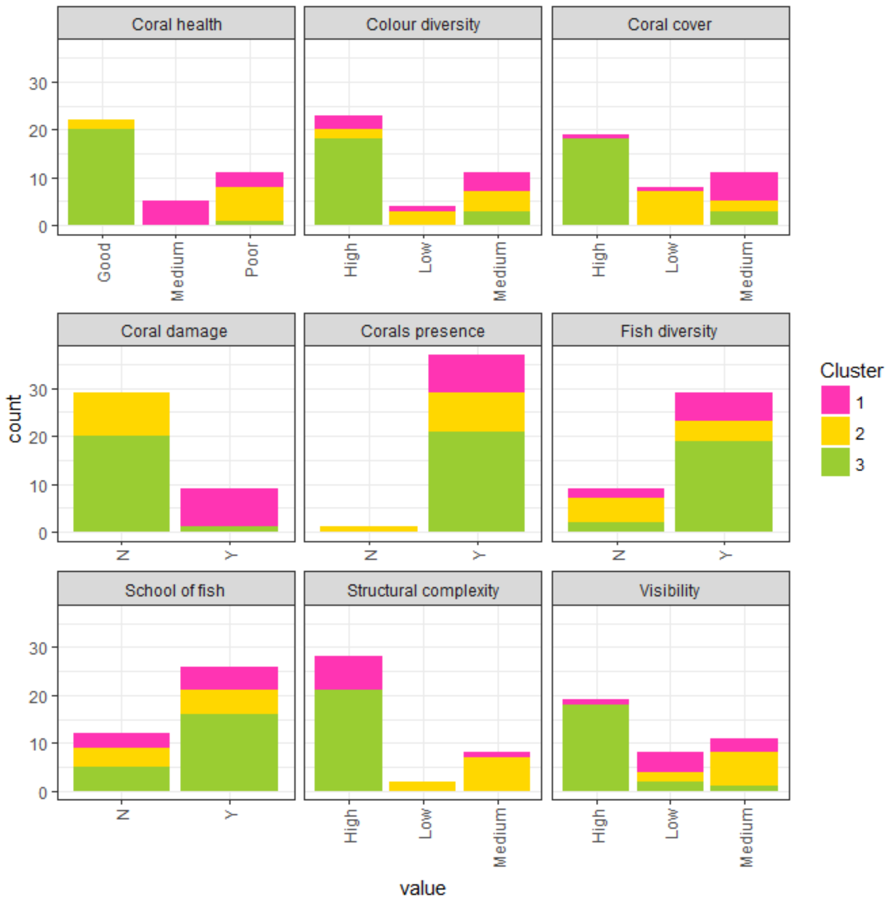


Figure 24 Breakdown of clusters by image attributes.

2.2.5.2 *Image selection*

Images were randomly drawn from the three clusters to build the reef aesthetic experiment. The design could accommodate a total of 150 participants; though the actual number of participants was only 105. In addition to the training image, four images were selected randomly for each participant (Table 9); one image each from Clusters 1 ($n = 8$ images) and 2 ($n = 9$), and two different images from Cluster 3 ($n = 21$). The selection was performed in such a way that each participant was shown a unique combination of images. The order of the non-training images was permuted randomly to ensure that the order in which the images were shown to the participants did not introduce bias. Thus, the study design provided for each non-training image to be elicited with a similar frequency and order within the sequences.

Table 9 XL Catlin Seaview Survey image identifier (ID), location, and cluster number for the images used in the aesthetics elicitation.

Image ID	Location (decimal degrees)	Cluster
291	(151.9897, -23.43459)	1
1387	(152.0832, -23.51289)	2
423	(151.9251, -23.30206)	2
3087	(147.6571, -18.80162)	1
3097	(147.7243, -18.66005)	2
4789	(147.5671, -18.59136)	1
5008	(147.4000, -18.25926)	2
5018	(146.0050, -16.41926)	3
5022	(145.8671, -16.24468)	3
5015	(145.8751, -16.24566)	1
4998	(145.9002, -16.23761)	3
4997	(145.9011, -16.20200)	3
5023	(145.8976, -16.19005)	3
5006	(145.8912, -16.17581)	3
5012	(145.8065, -16.13110)	1
5026	(145.8409, -16.04041)	3
5027	(145.8636, -16.03371)	3
5021	(145.8348, -15.94048)	2
5002	(145.7796, -15.51354)	1
4999	(145.6705, -14.66843)	2

Image ID	Location (decimal degrees)	Cluster
5001	(145.7874, -15.33826)	2
5020	(145.7106, -14.96368)	3
5016	(145.7028, -14.92913)	3
5005	(145.6660, -14.89462)	1
5007	(145.6912, -14.93310)	3
5014	(145.6151, -14.57202)	2
5028	(145.5353, -14.47206)	3
5025	(145.5285, -14.47063)	3
5019	(144.6500, -13.92386)	1
5017	(144.5258, -13.96996)	2
5003	(144.4167, -13.94287)	3
5011	(144.0725, -13.46171)	3
5009	(143.9280, -12.24109)	3
5000	(143.9321, -12.00700)	3
5010	(144.0276, -11.84304)	3
5024	(144.0976, -11.74772)	3
5004	(143.9759, -11.74704)	3
5013	(144.0958, -11.51201)	3

2.2.6 Elicitation in VR

Six Samsung smart phones (Samsung S5 and Samsung Note 6) were used for the experiment, using version 5.0 of the Android operating system. During the experiment, the phones were set to on flight mode and all applications other than the reef elicitation application were shut down to conserve battery power and to prevent overheating. Gear VR headsets from Oculus Rift were used to perform the VR experiments.

For each user to perform an elicitation for an image, a Quick Response (QR) code was generated to represent a unique combination of user ID and image ID, which was referred to as the media ID. The QR codes were generated by the web system and imported into R (R Core Team 2016) for inclusion in a survey booklet that, for each participant, contained the five demographics questions, a full page print-out of each of the 5 QR codes, and two template pages for manual recording of the participant's answers to the nine elicitation questions and the sureness value. These were recorded and subsequently used to double check the responses that were entered via the VR application and stored in the database. The participants scanned the QR code using a Samsung smart phone connected to the GearVR headset, which triggered the download of an image from the database. When they were finished with the elicitation for each image, the participant was prompted to submit their survey, which sent the data to the database.

2.3 The model

2.3.1 Potential covariates

In total, 5 demographic and 9 aesthetic questions were used as explanatory variables in the model (Table 10). Explanatory categorical variables were centred at 0 and calibrated to use specific categories as the model baseline. In addition, the middle-age range [26-45], the statement "I have never dived" and the male gender were used as baselines.

Table 10 Potential covariates considered in the Reef Aesthetics model.

Covariate name	Description
Demographics	
Group	Participant belongs to the Marine Scientist, Experienced diver or Citizen group
Gender	Gender of the participant
Young	Participant younger than 26 years of age
Old	Participant older than 45 years of age

Dive occasionally	Participant dives occasionally, less than or equal to one time per year
Dive often	Participant dives more than one time per year
Aesthetics Interview	
Q2. Hazy	Water quality - Is the image hazy?
Q3. Complexity	Structural complexity - Do the live corals on the reef form structurally complex habitats?
Q4. Damage	Damage on the reef - Can you see evidence of damage to the reef?
Q5. Colour	Colours – Is the reef mostly one colour?
Q6. Individual fish	Biodiversity - Do you see individual fish?
Q7. School of fish	Abundance - Do you see schools of fish?
Q8. Fish biodiversity	Biodiversity – Do you see more than one type of fish?
Q9. Biodiversity	Biodiversity - Can you see organisms other than corals or fish?

2.3.2 Model description

A hierarchical Bayesian model was used to estimate the probability that a reef is aesthetically pleasant as function of multiple questions *k*, images *j*, groups *g* and different levels of uncertainty *s*. Information on reef aesthetics was modelled for each elicitation *i* based on the explanatory variables described above, x_i:

$$y_i \sim Bernoulli(p_i)$$
$$logit(p_i) = \alpha_j + \sum_{k=1}^{5} \psi_k x_i + \sum_{k=1}^{8} \beta_{g,s,k}(x_i - 0.5)$$

$$\beta_{g,s,k} \sim N(\beta_{g,k}, \tau_{s,k}), \forall g \in 1 \ldots 3, \forall s \in 1 \ldots 3, \forall k \in 1 \ldots 8$$
$$\beta_{g,k} \sim N(\beta_k, \tau_{\beta_0})$$
$$\alpha_j \sim N(0, \tau_{\alpha_0}), \forall j \in 1 \ldots 39$$
$$\psi_k, \beta_k \sim N(0, 10^{-2})$$
$$\tau_{s,k}, \tau_{\beta_0}, \tau_{\alpha_o} \sim \Gamma(10^{-2}, 10^{-2})$$

Aesthetic indicator parameters, β, and demographic parameters, ψ, were considered differently. When the Aesthetic parameters were modelled for each question, the effects of group and uncertainty level were accounted in the estimation. At the higher model level, aesthetic parameters for each question, group and uncertainty were considered as random, with the mean estimated as function of groups, and variance components a function of uncertainty levels. The intercept parameter, α_j, was also random and estimated as a function of images with a variance term, τ_{α_0}. In contrast, the prior of the demographic parameters were considered as independent normal distributions. The R package rjags (Plummer 2016) was used to estimate model parameters.

The convergence of Markov Chain Monte Carlo (MCMC) chains was reached by using 90000 iterations, where 5000 were burin-in and 5000 were draws to infer on model parameters. Model residuals, posterior predictive checks and the Deviance Information Criterion (DIC; Spiegelhalter et al. 2002) were estimated and used for model selection. MCMC diagnostics from the coda (Plummer et al. 2006) package were used to check posterior distributions of model parameters.

The probability that an image was aesthetically pleasing was summarized using the quantiles of the distribution of the posterior probability for all the images. Images were assigned to 3 classes (Low, Medium and High) when their prediction values were below, between, or above the 2.5% and 97.5% quantiles, respectively.

2.4 Results

This section provides a description of the data and then a description of the results of the modelling.

2.4.1 Data description

A total of 105 participants were interviewed, representing a range of ages (18 to >45), gender (61% of men and 39% of women), and experience in scuba-diving. The largest number of participants belonged to the Marine Scientist group (37 participants), followed by the Citizens (36 participants) and the Experienced Diver group (32 participants), respectively. The training image was shown to all of the participants as the first image and the 38 other images were used on average 11 times, with a minimum of 4 and maximum of 19 elicitations.

Is the reef visually pleasing?

On average, the participants found most images aesthetically pleasing. At the group level, the Experienced diver was most likely to answer yes, while the Citizen group had the highest proportion of 'no' responses. In total, 60% of participants found the training image visually pleasant, and 39% indicated that there was a high level of uncertainty in their answer. Only one participant liked the training image with a low level of uncertainty. Interestingly, Experienced Divers never replied with low certainty, whereas the Marine Scientists were more likely to report with variable levels of sureness. Eight images were deemed visually pleasing across all groups, while only 1 image was found to be visually unpleasant by all participants. When we break the responses down by group, the Experienced Divers were the most unanimously positive with 17 images found to be visually pleasing; whereas the whole group of Citizens did not find 5 images visually pleasing (Figures 25-27).

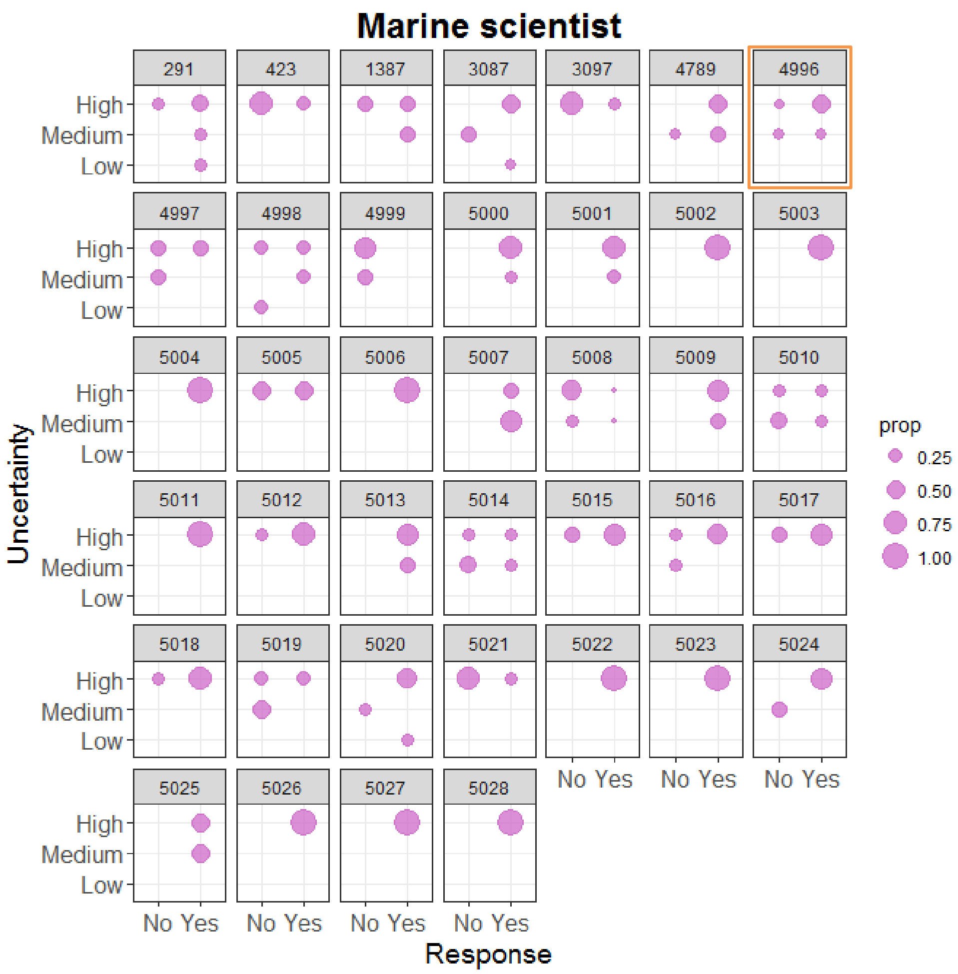


Figure 25 Proportion of responses for the Marine Scientist group to the question "Do you find this place visually pleasant", by image. The image in the orange box (4996) is the training image.

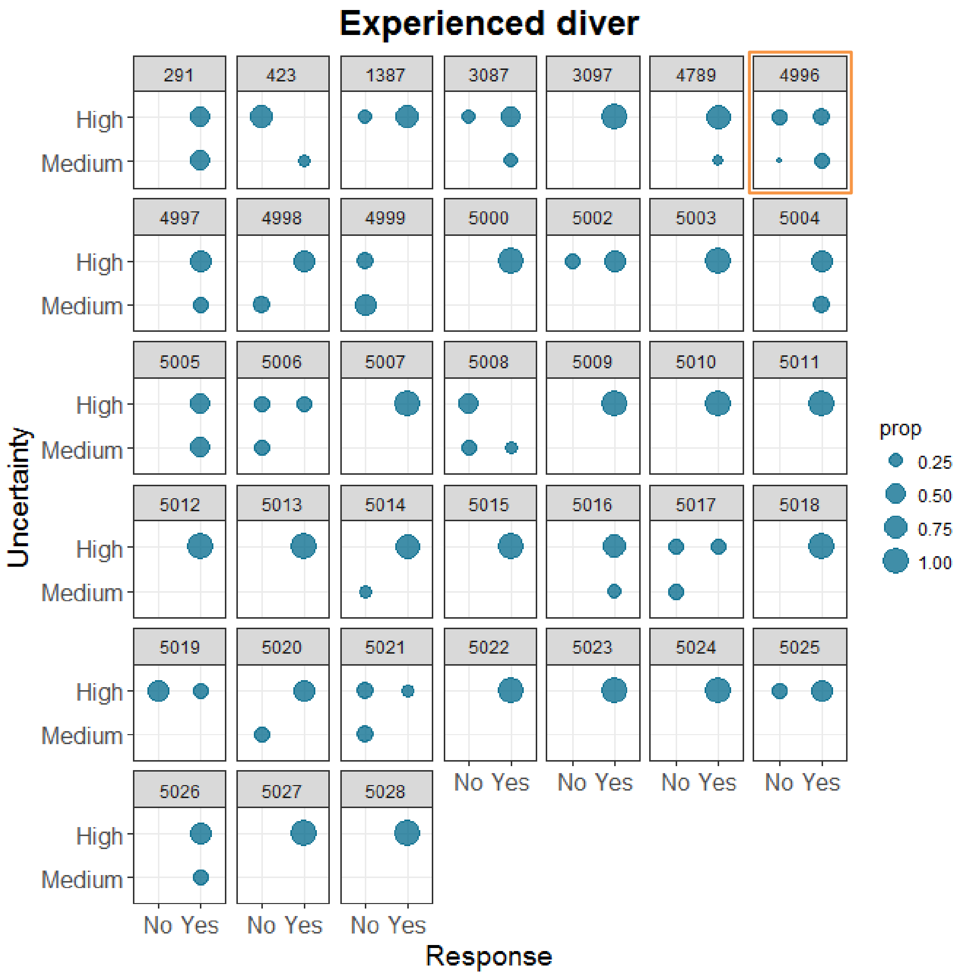


Figure 26 Proportion of responses from the Experienced Diver group to the question “Do you find this place visually pleasant”, by image. The image in the orange box (4996) is the training image.

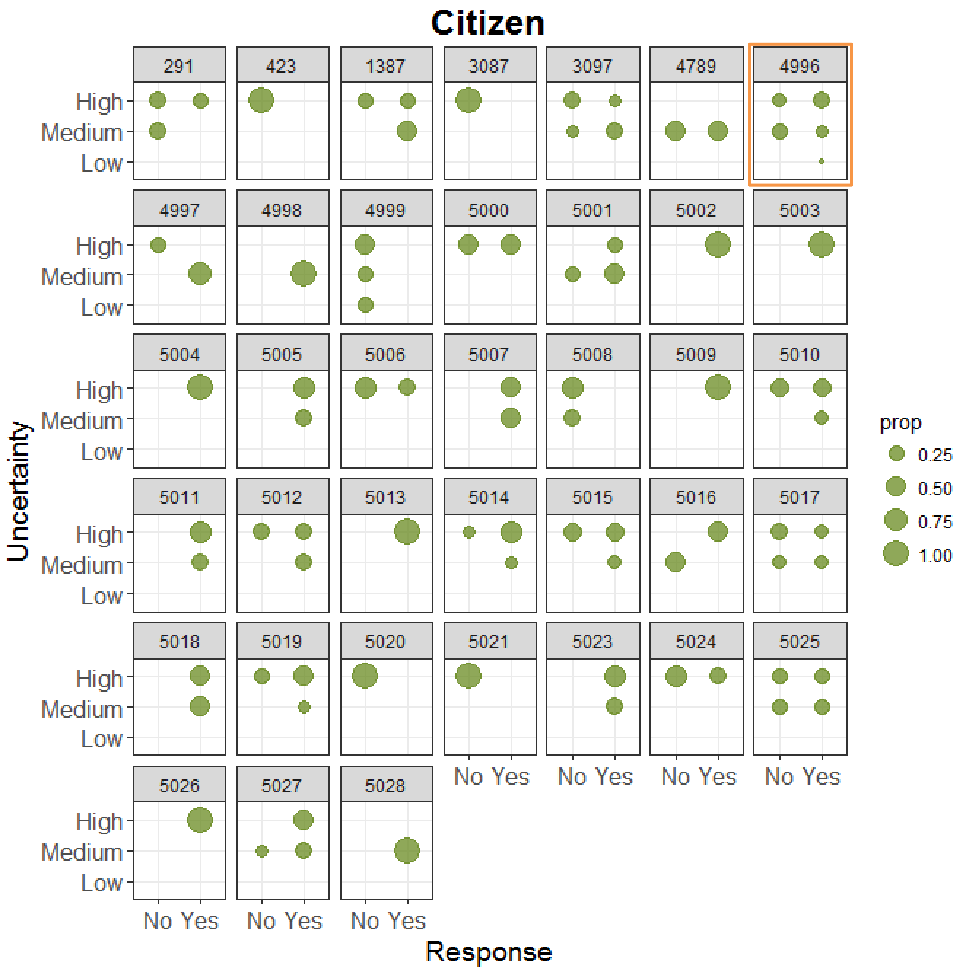


Figure 27 Proportion of responses from the Citizen group to the question "Do you find this place visually pleasant", by image. The image in the orange box (4996) is the training image.

Aesthetic indicator questions

Questions relating to the visual aesthetic indicators were answered with different levels of certainty across images (Figure 28). The detections of individual fish (Q6) and schools of fish (Q7) with high certainty were the two most common responses across all groups and images.

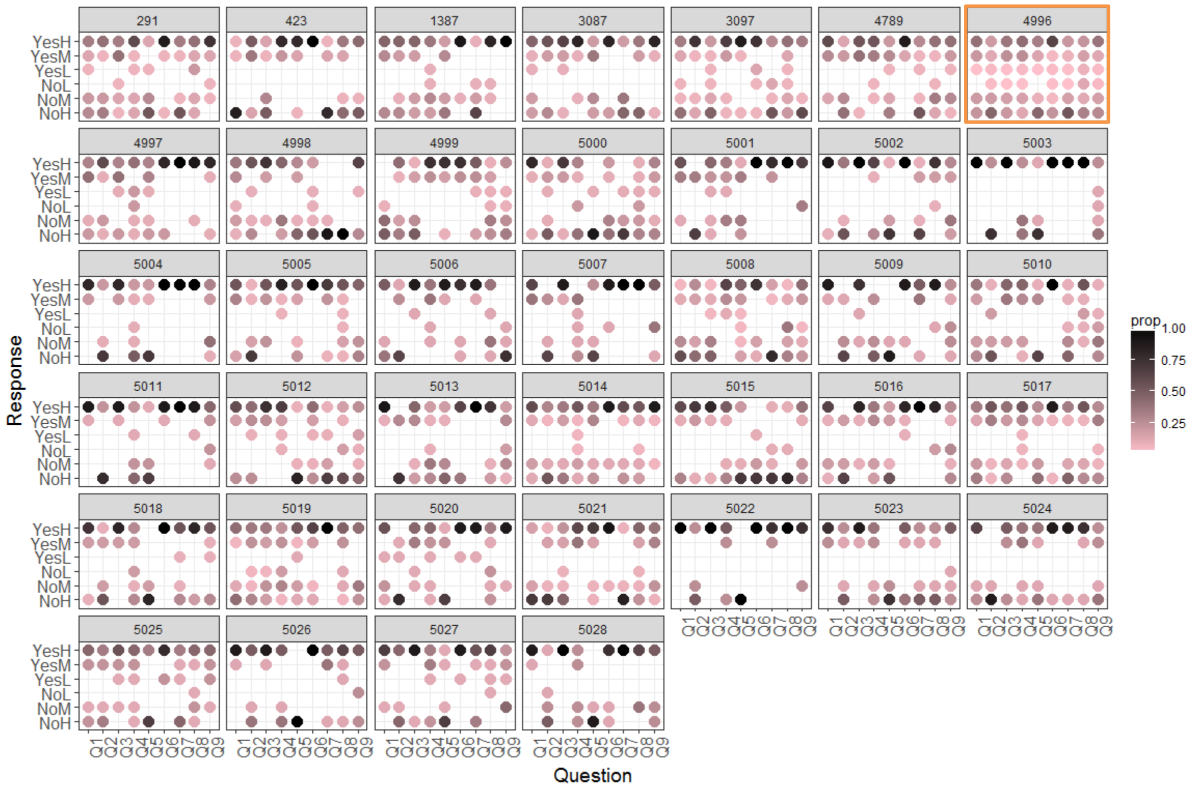


Figure 28 The proportion of responses to all of the interview questions. The image with the orange box around it was the training image.

2.4.2 Model predictions

Model predictions were classified into three groups that included a high, medium, and low probability of being visually pleasant. Most images that fell into the high probability class were found in the northern part of the GBR (Figure 29); although low and medium classes were found across the entire GBR. The class with a medium probability of being aesthetically pleasing included 19 reefs, while the low and high classes contained 10 reefs each. The highest probability that an image is aesthetically pleasing was 0.95 for the image 5028, while the lowest was for image 4999, with 0.17 (Figure 30). Image 5028 is from Cluster 3, which is characterized by high colour diversity, abundant fish, high coral cover without apparent damage and high levels of structural complexity and visibility. In contrast, image 4999 is characterized by low to medium structural complexity, poor to medium visibility, and low coral cover.

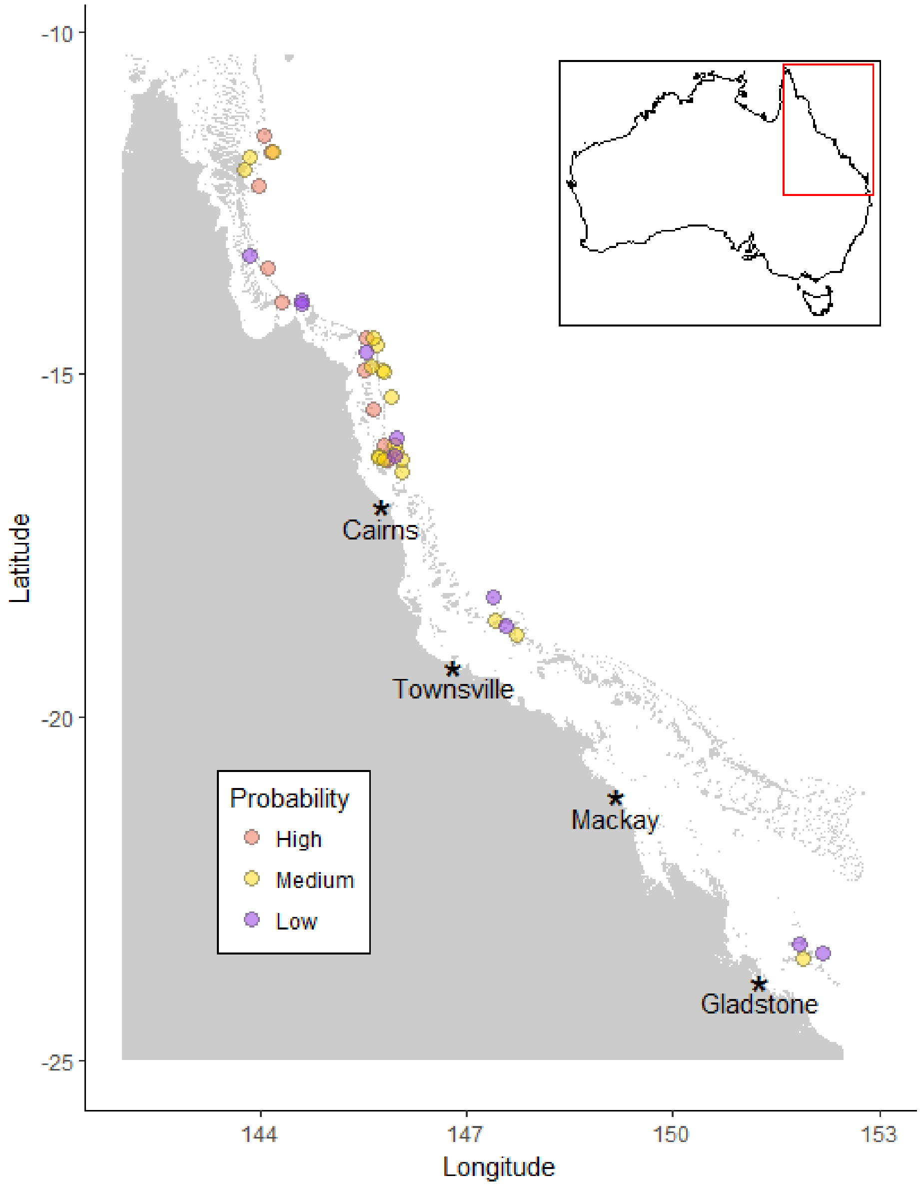


Figure 29 The spatial distribution of images and their associated probability of being aesthetically pleasing. Probability classes have been defined using the 2.5% and 97.5% quantiles of the posterior probability distribution. Image positions were jittered on the x-axis to reduce overlap.

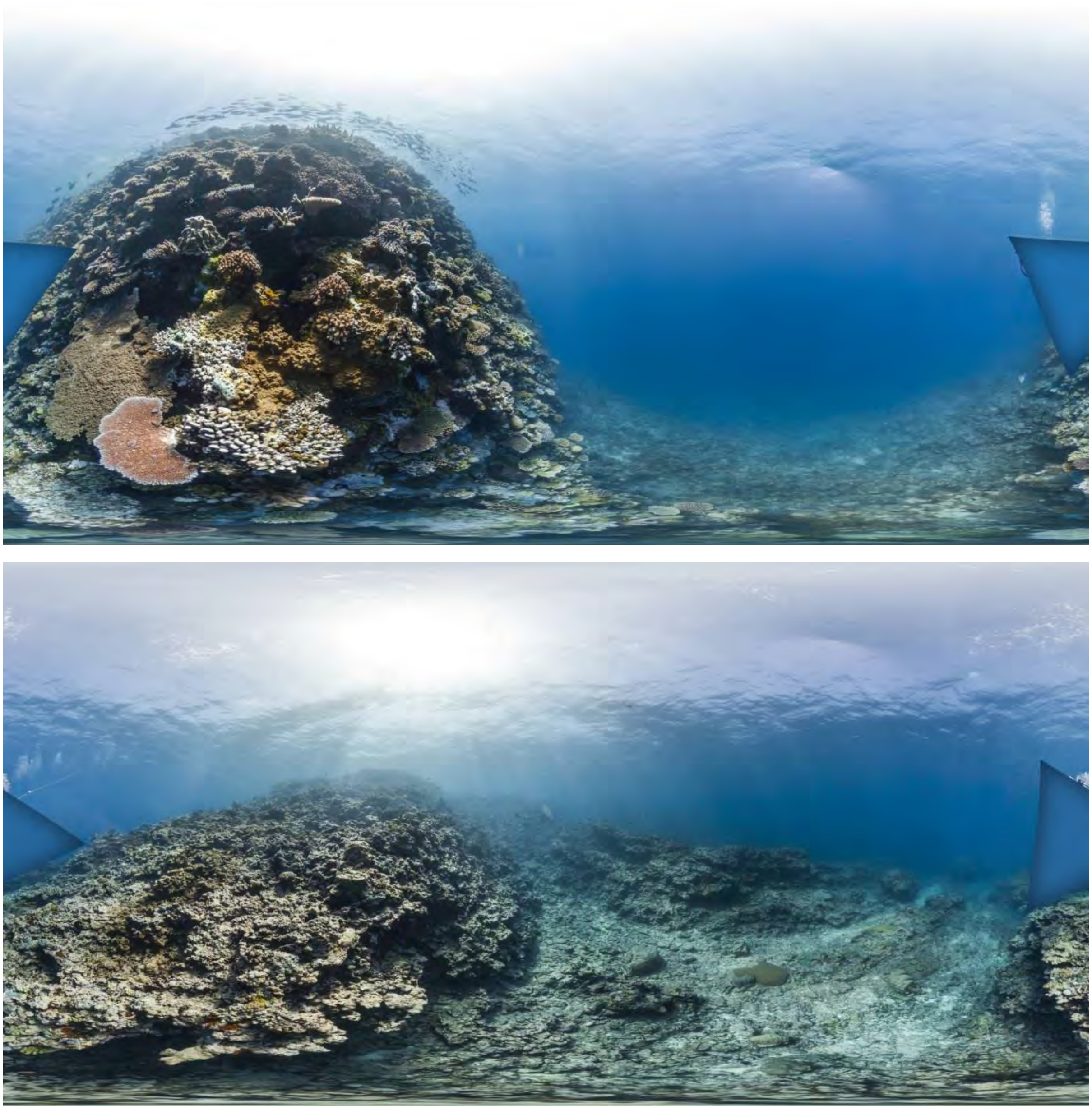


Figure 30 Images of the most (top panel) and least (bottom panel) aesthetically pleasing images in a equirectangular projection. Copyright XL Catlin Seaview Survey, see 360-degree images at these links: http://globalreefrecord.org/transect_explorer/12026/image/120261897/threesixty, http://globalreefrecord.org/transect_explorer/12035/image/120351218/threesixty

2.4.3 Estimation of reef aesthetic indicators

The explanatory variables were also extracted from posterior parameter distributions and summarized in terms of the mean and 95% credible intervals. In total, two aesthetic indicators were found to be significant in the model. The structural complexity question (Q3) was positively associated with perceived aesthetic value, while the question relating to reef colour (Q5) was negatively associated with aesthetic value. Note that a negative response to the colour question indicates that the reef is not uniform in colour (Figure 31), which suggests that participants preferred colourful reefs. The model also estimated negative effects for Haziness (Q2), Damage (Q4) and Biodiversity (Q9) and positive effects of fishes (Q6-Q8). However, the 95% credible intervals for these parameters included 0. These estimates are similar between the three groups (Figure 31). Participants younger than 26 years old were more positive in their responses. This was also true of occasional divers and participants from the oldest age class, but these effects also encapsulated 0. The model also estimated negative effects related to the female gender and for regular divers; but again, 0 was included in their 95% credible intervals (Figure 31).

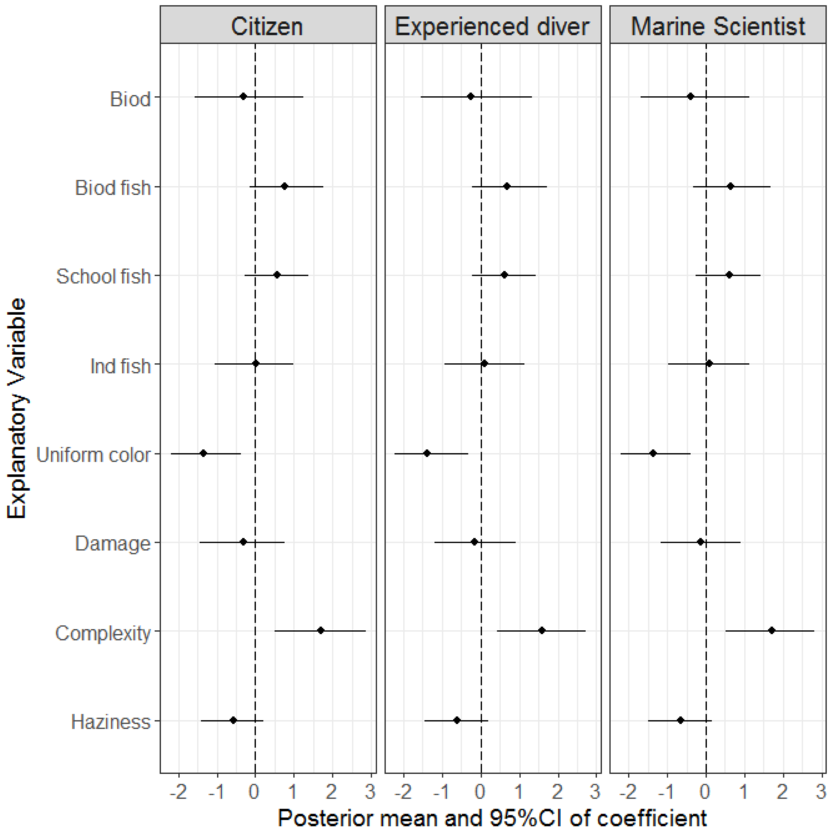


Figure 31 Statistical summary of model coefficients for each of the explanatory variables estimated by the reef aesthetic model, by group. Black dots represent the mean coefficient value and lines show their 95% credible intervals.

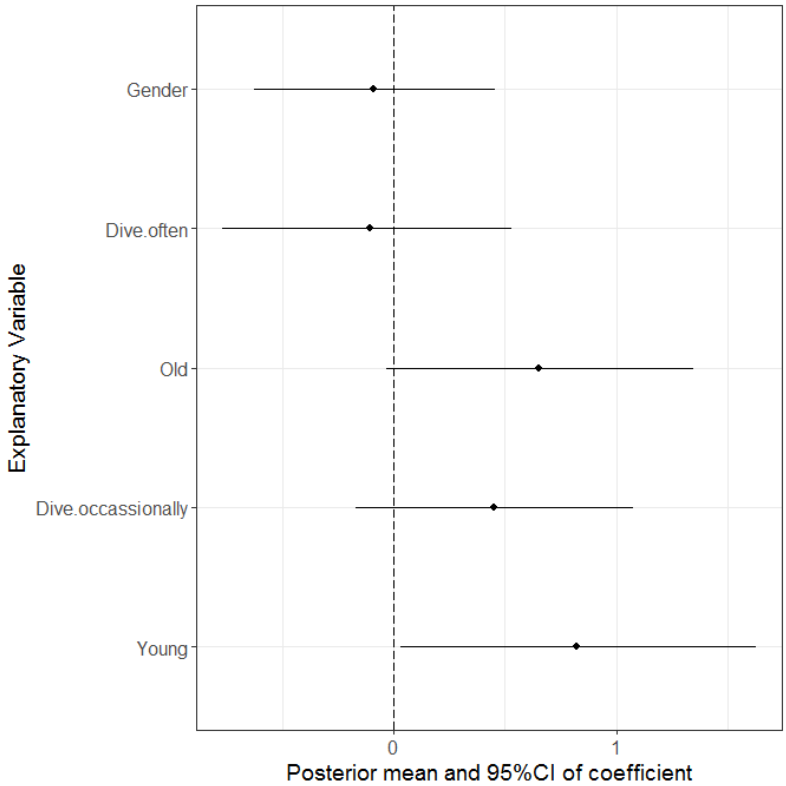


Figure 32 Statistical summary of the demographic parameters estimated by the reef aesthetic model. Black dots represent the mean coefficient value and lines show their 95% credible intervals

2.4.4 Model performance

Two approaches were used to estimate the goodness-of-fit of the model. First, we examined the distribution of the model residuals and did not find any evidence of outliers or lack-of-model fit (Figure 33). We also examined the relationship between the model residuals and the predictions and found that they were randomly distributed (Figure 34). Second, posterior predictive checks (PPC) were used to compare the lack-of-fit of the observed data with simulated datasets generated under the parameter estimates, which are considered as perfect (Gelman et al. 2014). Lack-of-fit is measured through the sum of squared residuals (SSQ) and was estimated for both the observed and simulated data independently. A relationship between the SSQ for the observed and simulated data shows that the SSQ for the simulated datasets is in the range 40-85, while the SSQ for the observed data only ranges between 60-80. This result indicates that the model potentially over-fits the data (Figure 35).

Two main model formulations were compared, the model with the group effect (Citizens, Experienced Divers, and Marine Scientists) as it was presented previously and a second model without a group effect. We compared the models and found that the model with the group effect had a lower DIC value than the model without the effect (445.9 and 463.4, respectively). This suggests that the group effect has some influence on the estimation of reef aesthetics values, even though the parameter estimates by group appear to be similar (Figure 31).

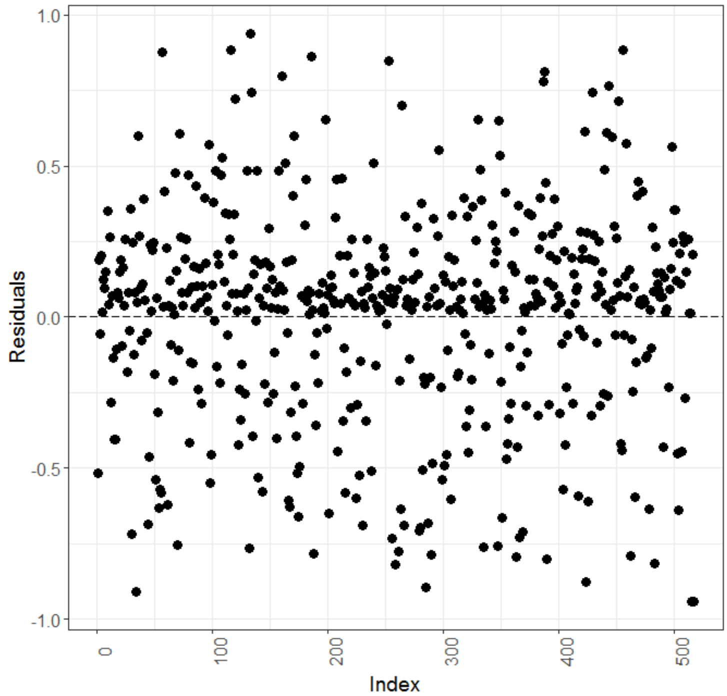


Figure 33 Distribution of the model residuals.

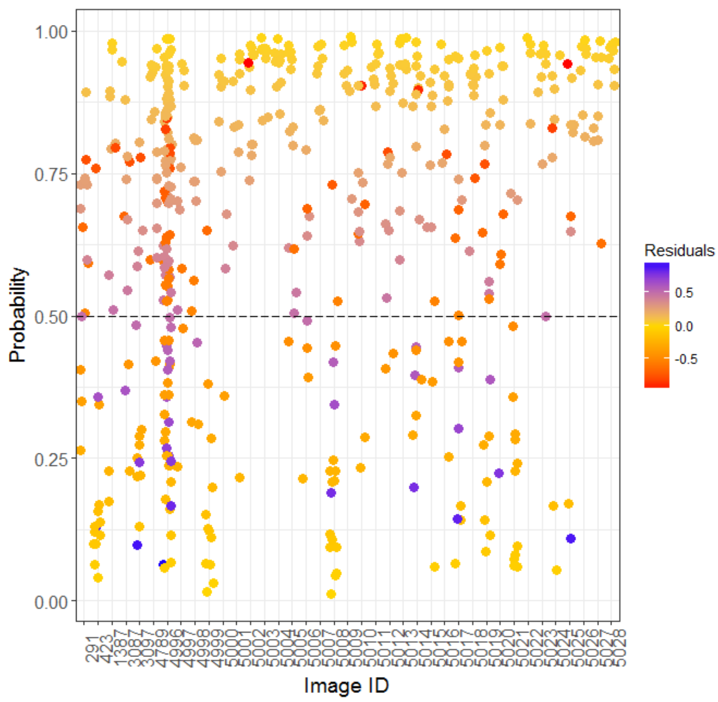


Figure 34 Estimated probabilities that an image is visually pleasant and their associated model residuals. Note that the points were jittered on the x-axis.

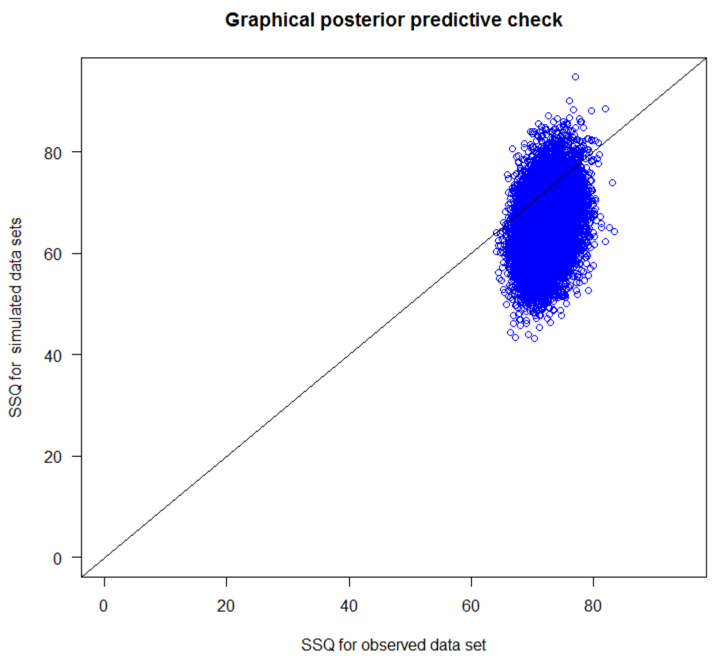


Figure 35 Posterior predictive check for the sum-of-squared residuals (SSQ) for the observed and simulated datasets.

2.5 Discussion

The use of virtual reality provides an innovative new way to tap into the human experience, allowing us to learn more about the particular characteristics that make a reef beautiful. In our experiment, we quantified the effects of nine- reef aesthetic indicators and used them to identify reef characteristics that people perceive to be aesthetically pleasing. We found that the structural complexity indicator and diverse colours strongly influence people's perception of beauty. Surprisingly, no statistically significant differences were found between the three groups of participants. This finding suggests that a person's past experiences in a reef environment do not directly influence their perception of the beauty. Interestingly, structural complexity is a reef-heath indicator (Mumby and Steneck 2008). Marine Scientists would be aware of this and therefore, their perception of the beauty may have been linked to what they perceive as a healthy reef; in fact, the language used by the Marine Scientists suggested this during the interviews. However, Citizens and Experienced divers would be less likely to know what contributes to reef health, and yet they also deemed structurally complex reefs as visually pleasing. Thus, we infer that structural complexity is both an indicator of aesthetic value, as well as reef health. In contrast, the diversity of colours is not monitored during reef-health surveys. Therefore, including an assessment of reef aesthetic indicators related to colour would add an important additional dimension to management and conservation efforts in the GBR.

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- Australian Institute of Marine Science (http://aims.gov.au/)
- Reef Check Australia (www.reefcheckaustralia.org/)
- University of Queensland (UQ) Remote Sensing Research Centre (https://www.gpem.uq.edu.au/rsrc)
- UQ Global Change Institute (http://www.gci.uq.edu.au/)
- XL Catlin Global Reef Record (http://globalreefrecord.org/home_scientific)

2.7 References

DeGeorges, Andre, Thomas J. Goreau, and Brian Reilly. 2010. "Land-Sourced Pollution with an Emphasis on Domestic Sewage: Lessons from the Caribbean and Implications for Coastal Development on Indian Ocean and Pacific Coral Reefs." Sustainability 2 (9):2919.

Gelman, Andrew, John B. Carlin, Hal S. Stern, David B. Dunson, Aki Vehtari, and Donald B. Rubin. 2014. Bayesian Data Analysis. 3 ed: Chapman and Hall.

Johnston, C, A Smith, and J Dyke. 2013. Defining the aesthetic values of the Great Barrier Reef. Townsville, Australia: Great Barrier Reef Marine Park Authority.

Lucas, P.H.C., T. Webb, P.S. Valentine, and H. Marsh. 1997. The outstanding universal value of the Great Barrier Reef World Heritage Area. Townsville, Australia: Great Barrier Reef Marine Park Authority.

Mumby, Peter J., and Robert S. Steneck. 2008. "Coral reef management and conservation in light of rapidly evolving ecological paradigms." Trends in Ecology & Evolution 23 (10):555-563. doi: https://doi.org/10.1016/j.tree.2008.06.011.

Plummer, Martyn. 2016. rjags: Bayesian Graphical Models using MCMC. R package version 4-6. https://CRAN.R-project.org/package=rjags

Plummer, Martyn, Nicky Best, Kate Cowles and Karen Vines. 2006. CODA: Convergence Diagnosis and Output Analysis for MCMC, R News, vol 6, 7-11.

Pocock, Celmara. 2002. "Sense matters: aesthetic values of the Great Barrier Reef." International Journal of Heritage Studies 8 (4):365-381.

R Core Team. 2016. R: A Language and Environment for Statistical Computing 3.3.1. R Foundation for Statistical Computing, Vienna, Austria.

Spiegelhalter, David J, Nicola G Best, Bradley P Carlin, and Angelika van der Linde. 2002. "Bayesian measures of model complexity and fit." Journal of the Royal Statistical Society B 64:583-639.