Cooperative Research Centre for Coastal Zone, Estuary & Waterway Management

Technical Report 76

Remote sensing for coastal ecosystem indicators assessment and monitoring

Maps, techniques and error assessment for seagrass benthic habitat in Moreton Bay

Stuart R. Phinn, Chris M. Roelfsema
Arnold G. Dekker, Vittorio E. Brando
Janet Anstee & Paul Daniel

March 2006

The University of Queensland
Australia

CSIRO

CRC for Coastal Zone
Estuary & Waterway Management

Remote sensing for coastal ecosystem indicators assessment and monitoring

Maps, techniques and error assessment for seagrass benthic habitat in Moreton Bay

Stuart R. Phinn and Chris M. Roelfsema

Centre for Remote Sensing and Spatial Information Science

Centre for Marine Studies

School of Geography, Planning and Architecture

The University of Queensland

Arnold G. Dekker, Vittorio E. Brando, Janet Anstee and Paul Daniel

Environmental Remote Sensing Group

Division of Land and Water

CSIRO

31 March 2006

CRC for Coastal Zone Estuary & Waterway Management

Remote sensing for coastal ecosystem indicators assessment and monitoring
Maps, techniques and error assessment for seagrass benthic habitat in Moreton Bay

Written by:
Stuart R. Finn
Chris M. Roelfsema
Arnold G. Dekker
Vittorio E. Brando
Janet Anstee
Paul Daniel

Published by the Cooperative Research Centre for Coastal Zone, Estuary
and Waterway Management (Coastal CRC)

Indooroopilly Sciences Centre
80 Meiers Road
Indooroopilly Qld 4068
Australia

www.coastal.crc.org.au

National Library of Australia Cataloguing-in-Publication data
Remote sensing for coastal ecosystem indicators assessment and monitoring
Maps, techniques and error assessment for seagrass benthic habitat in Moreton Bay
QNRM06307
ISBN 1 921017 55 4

Acknowledgements

Coastal CRC for funding our work for the past six years, and their administration and science staff for letting us do this, and being patient while we took longer than expected.

Professor Justin Marshall for linking his ARC Linkage project 2003–2007 with our project to enable an expansion in the scope of image and field data able to be collected for Moreton Bay.

Field assistance from Lindsay Banin, Alan Goldizen, Ian Lieper, Kylie Jennings, Justin Marshall and Rob van Ede.

Data and image processing assistance from Katherine McMahon, Ian Leiper, Wes Leedam and Lindsay Banin.

Seagrass watch volunteers who completed the seagrass biomass measurement.

All of the staff at the University of Queensland's Moreton Bay Research Station.

Nicola Udy and all of the other Queensland Parks and Wildlife Service staff who assisted with the field survey and map production.

Ben Longstaff and EHMP staff for field survey and data processing.

The Port of Brisbane Corporation for provision of image and field data covering the Fisherman Islands region.

The School of Geography, Planning and Architecture and Centre for Marine Studies at the University of Queensland for our research infrastructure.

Table of contents

List of figures

List of tables

Non-technical summary

Key components of the project

The purpose of this project was to develop, implement and validate approaches for mapping benthic habitats in Moreton Bay using commercially available remote sensing information and field survey. Due to the focus of monitoring and management programs in the Bay on seagrass properties, notably seagrass density and species composition, the project was confined to mapping this benthic habitat. In the process of deriving maps of seagrass properties, other benthic substrates (e.g. coral and algae) were mapped but not included in the final products. The techniques and data we used were confined to the shallow and clear areas of the Bay, which were also the areas where seagrass was commonly found. There were three main activities in the project:

(1) Collection, integration and storage of field survey (seagrass species, density and biomass) and image (satellite and airborne) data for seagrass in Moreton Bay in 2004 to produce a map of seagrass density across all of Moreton Bay for use by government agencies

(2) Processing of airborne and satellite image data for select Moreton Bay sites to produce maps of seagrass species composition, density and above-ground biomass

(3) Validation of seagrass species composition, density and above-ground biomass maps against field survey data collected at the same time as image data to determine the level of accuracy for different types of commercially available image data.

Conclusions of the project

Our results show how the most commonly available types of remotely-sensed data sets from airborne and satellite images can be used by scientists and managers to produce accurate maps for monitoring seagrass properties relevant to inventory and monitoring activities in coastal water bodies. The most detailed and highest accuracy maps, in terms of seagrass species composition, density (percentage cover) and biomass were obtained from **airborne** hyperspectral image data, closely followed by high-spatial resolution **satellite** multispectral image data. Satellite image data still provided sound results for mapping seagrass density and biomass, but lacked the spatial (small enough pixels), spectral (suitable wavelengths) and radiometric (sensitivity to light levels) resolutions to deliver more detailed maps.

Significance of the project to stakeholders

The main beneficiaries of this work will be managers, scientists and technicians, who require information on seagrass distribution and its properties in Moreton Bay. More generically, our findings will benefit those who need to know which type of image data set and processing approach are required for mapping seagrass properties across a range of water clarity levels in sub-tropical coastal environments. In a local context, the maps produced are being used by the Ecosystem Health Monitoring Program (EHMP—Moreton Bay Waterways and Catchments Partnership) and Queensland EPA's Marine Parks divisions for monitoring and management. We have commenced discussions with EPA/EHMP on how to incorporate the techniques developed in this work into their regular monitoring program.

Key outcomes (actual and potential)

This project has demonstrated the benefit of inter-agency collaboration for collecting, processing, mapping and disseminating spatial information (maps of seagrass properties) for natural resource science, monitoring and management. At the time of writing this report the authors are discussing how to continue this approach with the agency responsible for seagrass monitoring and management in Moreton Bay, to reduce the amount of field survey they undertake and to provide a spatially complete coverage of Moreton Bay. Our results provide an urgently needed baseline data set for seagrass density across Moreton Bay, which has been distributed as the standard state government base-map for seagrass in Moreton Bay. The maps of seagrass species composition and biomass across the Eastern Banks are research products and have been placed in a commonly accessible format for science, monitoring and management agencies to investigate further.

Our project provides the first international, fully objective evaluation of the accuracy of a range of commercially available image data sets and the full range of processing techniques from simple to complex, to produce maps of seagrass properties. The results from this comparison will enable mapping technicians, scientists and managers to objectively select the image and field data and processing technique most suited to a specific environment and seagrass mapping and monitoring problem. Our results also make a significant contribution to seagrass ecology and remote sensing science. Findings will be used demonstrate which image/data processing technique combination is most suitable for mapping seagrass properties.

Recommendations for future research and development and for further adoption of the research by stakeholders

Completion and refinement of the web-based toolkit for mapping coastal environments from remotely sensed data (http://www.coastal.crc.org.au/rstoolkit/index.html). We expect this toolkit to be continually updated as our knowledge, technique and skill bases grow, and see it as a repository for our work and as a critical tool for educating groups with which we work. We also expect to use this approach as part of our World Bank GEF Coral Reefs project to communicate the most suitable mapping methods to management agencies in developing countries.

The image and field data sets collected in Moreton Bay will provide the basis for an international evaluation of the best practice in optically shallow remote sensing methods for depth, water quality and substrate cover types. This project is obtaining funding from The United States Official of Naval Research, The University of Queensland and CSIRO. We are in the process of submitting an ARC Linkage International proposal to support an international workshop where all groups invited will process the Moreton Bay data using their approaches and then validate results using field data. An analysis will then be conducted to determine the most accurate algorithms.

The field survey techniques that were refined as part of this work have become the basis for a benthic survey manual which we are in the process of preparing with the Great Barrier Reef Marine Park Authority and the Australian Institute of Marine Science to have adopted as a standard method. We are also working with these groups to develop operational mapping applications to monitor the extent and change in extent of live and dead coral over the entire Great Barrier Reef. The method has been endorsed by several groups involved in benthic cover surveys in reef and seagrass environments, and our manual is linked to their websites as a guide for field survey (http://www.nova.edu/ocean/cpce/).

The image and field data sets collected for this project are unique and will allow a new perspective to be taken on seagrass spatial ecology and physiology. The data delivered to the UB (Urban Benthic) Project as part of our work, is a start of this type of approach where seagrass species and structural (density, biomass) information will be used to understand ecological, physiological and biochemical processes in seagrass environments. We are in the process of designing projects that will include seagrass physiologists. A key gap in our knowledge is if and how we can use remote sensing for sparse seagrass meadows, and we have just commenced a project with the Reef CRC on that.

Chris Roelfsema's doctoral research will build on the results presented in this work and further examine the role that different levels of image processing have on the accuracy of benthic cover maps in areas of varying water clarity. This work will be continued in developing countries through the south-west Pacific.

We would desperately hope to continue the application of the image processing techniques developed in Phase 1 and Phase 2 of our work for monitoring water quality and benthic habitat. Unfortunately there have been very limited opportunities to do so, and we would strongly recommend funding for this type of work given its potential to be used across all levels of government from local to national scales in monitoring and managing coastal environments.

1 Introduction and background

The first component of this remote sensing project was carried out as a Phase 1 Coastal CRC sub-project. The Phase 1 project developed and tested several algorithms as a demonstration phase for mapping key environmental variables in the coastal zone and collected extensive field and image data sets in each Regional Study Area. This project (Phase 2) intended to integrate the approaches developed in Phase 1 with key environmental indicators and modelling needs, to develop and validate benthic cover type maps for Moreton Bay. The approaches used were integrated into a toolkit of image and field based approaches for mapping and monitoring key coastal ecosystem health indicators. The project team has worked with South-East Queensland Coastal CRC regional sub-projects (UB: Benthic Habitat Function and Nutrient Processing) and management agencies (Queensland Environmental Protection Agency, Port of Brisbane Corporation) to deliver relevant spatial information for mapping and monitoring Moreton Bay. We have combined these approaches in an interactive instructional tool for managers or scientists to use for integrating remote sensing into monitoring and management schemes (http://www.coastal.crc.org.au/rstoolkit).

The research question driving this section of the SR project was: How can remotely sensed data sets be used by scientists and managers to produce accurate spatial information relevant to mapping and monitoring key coastal ecosystem health indicators in coastal water bodies and aquatic vegetation? Due to the focus of monitoring and management programs in the Bay on seagrass properties, notably seagrass density and species composition, the project was confined to development and assessment of techniques for mapping this benthic habitat.

2 Need

The aim of this project was to address stakeholder requirements for regularly updated maps of coastal environments, in particular, maps showing aquatic vegetation (seagrass). Presently, there is not an established and verified combination of field and image data, and processing techniques to deliver maps of benthic cover types and their associated properties, e.g. seagrass density (percentage cover) and biomass, in coastal environments. Commonly available imaging technologies, including airborne data, high spatial resolution satellite image data (pixel size < 5 m) and moderate spatial resolution satellite image (pixel size 10 m – 30 m) data have been applied in separate studies. There has not been a systematic evaluation of these data sets and current state-of-the-art mapping algorithms across the range of water clarity and depths commonly found in coastal estuaries and embayments. Part of the reason for this has been the lack of suitable field data to use for validation of the map products.

This project obtained an internationally unique field data set from Moreton Bay through the cooperation of several government agencies and private companies with the UQ/CSIRO CRC remote sensing team. This data set contains georeferenced measurements of seagrass species composition, percentage cover (density) and biomass. These data were stored in a GIS and used to evaluate the accuracy of several different image types and processing approaches for mapping benthic cover. An integrated map of seagrass density was also derived for all of Moreton Bay from field and image data sets. The output maps of seagrass density, species composition and biomass were provided in a format required by scientists and management agencies to understand how coastal systems are changing and to maintain them.

These maps will be used by other groups within the CRC, the Queensland Department of Primary Industries and Fisheries' Resource Condition and Trend Unit and the Queensland Environmental Protection Agency's (EPA) Marine Parks Division, and the Moreton Bay Waterways and Catchments Partnership's (the Partnership) Ecosystem Health Monitoring Program (EHMP). This activity required an extensive base of georeferenced field survey, airborne and satellite image data sets. The mapping algorithms developed in the Phase 1 CRC project were applied to produce a series of substrate type images (if they were seagrass maps then it is better to state that, but if they really were benthic substrate maps then we need to clarify earlier text, which implies that only seagrasses were mapped) maps for use by the SEQ Benthic Habitat Assessment project. Preliminary contact with other stakeholders in the area (the Partnership, Queensland Department of Primary Industries, Queensland Parks and Wildlife) indicated they will also require benthic maps to be produced from this project.

The main stages of this activity included:

- collation of all spatial and image data and substrate mapping algorithms for selected benthic cover sites in Moreton Bay
- design and implementation of workshops for the stakeholders and scientists in the SEQ Benthic Habitat sub-project and other government agencies on potential products and key areas to focus on
- processing of airborne and satellite image data for select Moreton Bay sites to produce and verify maps of benthic substrate type, density and biomass.

The following two tasks were not completed as the time taken to process the individual images coinciding with the July–August 2004 field data collection took a lot longer than expected, and we were able to produce more map products at a higher level of accuracy. We intend to complete these between June and September 2006, and will continue our research using the data sets collected in this project, and work with key agencies to integrate our techniques into their monitoring programs.

- Production of substrate change maps and identification of factors causing the change
- Design and implementation of final workshop for stakeholders and scientists in the SEQ Benthic Habitat sub-project and local stakeholders to present mapping results and implications for developing mapping tools.

3 Objectives

The objectives of this project were to produce and verify maps of benthic substrate cover types, with a focus on seagrass and its biophysical properties for sections of Moreton Bay using airborne and satellite image data sets.

The secondary objectives of this project were:

(1) to collect and deliver in a georeferenced GIS, set of field survey data on seagrass species, density and above-ground biomass for as many sites in Moreton Bay as possible

(2) to collect and deliver georeferenced, atmospherically and air–water interface corrected, airborne hyperspectral (CASI-2) and satellite multi-spectral (Quickbird-2, Landsat 5 TM) images for Moreton Bay during the same period that field survey data were collected

(3) to process the corrected image data sets to produce maps of seagrass density, seagrass species composition and above-ground seagrass biomass for specific sections and all of Moreton Bay

(4) to process the corrected airborne hyperspectral data to map water depth, water quality and substrate cover types

(5) to estimate and evaluate the accuracy level of each image-seagrass map product based on direct comparison of image maps to field survey data for the relevant seagrass and environmental properties.

4 Approach and methods

The central goal of this project was to produce accurate maps of benthic habitat, specifically seagrass habitat, in Moreton Bay using a number of commercially available data sets and verify these against a detailed and extensive field data set. Figure 1 outlines the sequence of data collection, pre-processing, mapping and validation that was used. The methods used represent a range of standard and highly advanced image processing techniques and also include new field survey techniques, all of which are used for mapping submerged aquatic vegetation. Mapping of seagrass density, species composition and biomass was done using standard image classification techniques applied to all of the airborne and satellite image data sets. These techniques all performed well when limited to specific water depths and levels of water clarity, with the airborne hyperspectral data showing the highest accuracy. Mapping of depth, water quality and substrate type over depths > 4 m required airborne hyperspectral data and a new physics-based mapping approach developed by Arnold Dekker’s group at CSIRO. The final products are maps of each seagrass property (species composition, density and biomass), mainly for the Eastern Banks area, which have been validated. Data on seagrass density was collected throughout the Bay by multiple agencies, in addition to the maps produced from Landsat 5 TM. This allowed production of a Bay-wide map of seagrass density. Additional work, building on the data sets collected and processed as part of this project is being built through: (1) an ARC Linkage project of Phinn, to evaluate the use of new mapping approaches; and (2) Roelfsema’s doctoral thesis, which assesses changes in benthic cover map accuracy as a function of different levels of atmospheric correction and its effect across a gradient of water clarity.

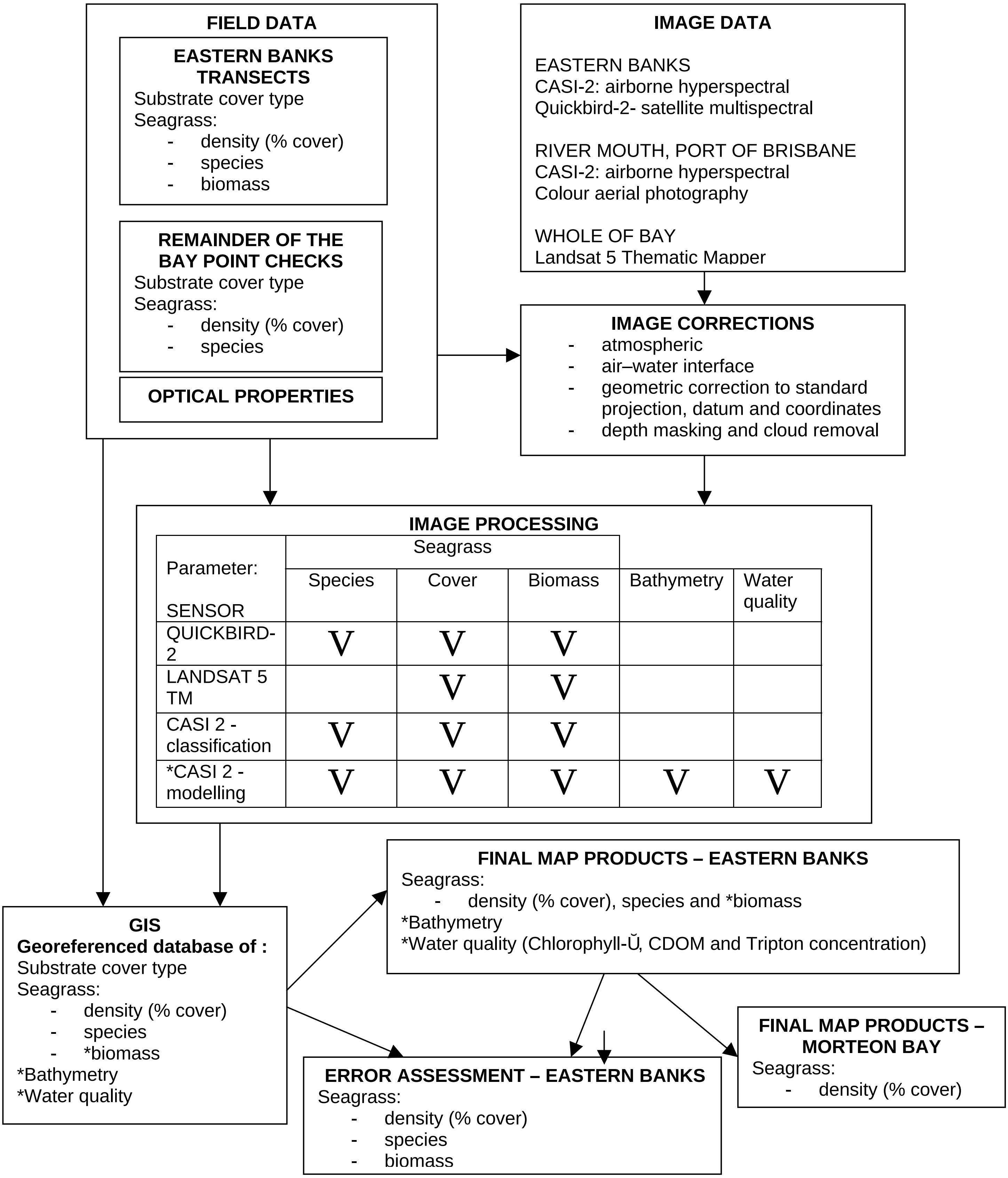


Figure 1. Overview of data collection, processing and analysis methods for mapping Moreton Bay (seagrass density) and Eastern Banks. * indicates a preliminary method and product.

4.1 Moreton Bay field survey

4.1.1 Site selection

The field data collection was a collaboration between a variety of organisations that all required to have seagrass maps for parts or the whole of Moreton Bay. This resulted in a division of the area (shallow clear water, turbid and or deep waters and Fisherman Islands region) and survey by different organisations in each area (CRC survey team, EHMP & EPA teams, and Port of Brisbane Corporation (POBC)). Ideally all the methods used would be the same, but due to the requirements of the different organisations a variety of approaches were applied to determine seagrass species composition and density. These methods were video and snorkel spot check, quadrat surveys and photo transects surveys. Locations of survey sites in areas other than the Fisherman Islands region were planned using a recently acquired Landsat 5 TM image and seagrass maps from Hyland et al. (1989). Sites were chosen to represent locations which showed a potential change in seagrass cover. The region around Fisherman Islands had to be mapped as part of the Port of Brisbane Corporation's port extensions reporting commitment. The sites visited in this region were based on their previous survey design.

4.1.2 CRC Survey

In the clear shallow waters (the Eastern Banks region) detailed information was gathered using hundred-metre long benthic photo transect surveys. Hundred-metre transects were deployed on the benthos at sites, at depths < 3.0 m. Swimming along the transect, a snorkeller then captured, at two-metre intervals, a photo of the benthos at 0.5 m from the bottom. The photo was captured using a Sony Cybershot digital camera in a marine-pack housing with a 16 mm wide-angle lens. The location of transects was primarily determined to ensure that a change in seagrass species and or density would be detected. The location of the transect was logged every five seconds through a handheld Garmin 72 GPS, floating in a drybag towed by the snorkeller.

Photos were analysed using an image viewing/interpretation program (Coral Point Count, http://www.nova.edu/ocean/cpce/) and Microsoft Access database. Twenty-four points were placed on each photo in a regular grid. For each point in the photo, seagrass species and bottom type was determined. Percent cover or density was calculated as a percentage of the 24 points per photo containing seagrass. The results of each photo were linked to GPS coordinates using ArcView. These results could then be plotted on the remotely sensed imagery.

4.1.3 Queensland Parks and Wildlife Service—Marine Parks and Ecosystem Health Monitoring Program

In the turbid or deep waters, spot-check surveys were conducted using a video camera dropped from the side of the boat just above the seabed. Real-time images were directly analysed using a monitor in the boat and information about substrate, seagrass species and/or percentage cover was stored with real-time coordinates on a laptop. Coordinates were determined using a handheld GARMIN GPS. The edge of the seagrass bed was followed and automatically logged. Video surveys could not be done with a speed higher than 3kn therefore the camera would be retrieved and boat would travel to the next site. Since not all boats were equipped with a video, a snorkeller would enter the water and snorkel over the benthos for about 10 m. After surfacing, the snorkeller would note the seagrass species composition and visually estimate density. No further analysis was needed since the species composition and density data were determined for each site in the field.

4.1.4 Port of Brisbane Corporation

In the Fisherman Islands region a combination of drop-down video and 10 m snorkel transects was applied. As some of the boats did not have a video camera, a snorkeller would enter the water and snorkel over the benthos for about 10 m. After surfacing, the snorkeller would note the seagrass species composition and density from a visual estimate only.

4.1.5 Optical properties of Moreton Bay waters

Inherent and apparent optical properties of Moreton Bay waters in winter were measured as part of the fieldwork campaign, which was undertaken to coincide with image acquisition and our other field surveys from 27 July to 3 August 2004. This survey covered sites from the Coastal CRC 2001 field sampling and additional sites (Phinn et al. 2004). These properties defined the scattering and absorption characteristics of the water column (IOP) and actual incident light conditions (AOPs).

The aim of the fieldwork was to collect in situ data from Moreton Bay in winter for both model parameterisation and validation. Effort was placed on characterising the (variations in) optical properties of the water column at several locations in Moreton Bay. These optical properties are required in order to conduct high-level processing of remote sensing data of water bodies, in particular the extraction of depth, water quality parameters and substrate reflectance. Furthermore, substrate cover type reflectance spectra were collected in order to expand the CSIRO Land and Water spectral library.

In situ absorption, attenuation, backscattering, reflectance and vertical attenuation were measured at 20 locations (see Figure 7), and water samples were collected for measuring in vivo absorption of CDOM, chlorophyll and tripton as well as the tripton and chlorophyll concentration. When possible, reflectance spectra of substrate, algae species and epiphytic growth where also measured. Further details on the data and the methodology used for this sampling can be found in section 2.2.3 of Coastal CRC Technical Report No. 28 (The Fitzroy River Estuary and Port Curtis Phase I report, Dekker et al. 2005).

Table 1 and Table 2 report on conditions measured at the 20 sampling sites during the field campaign.

In Table 5, the range of the IOPs (Inherent Optical Properties) and SIOPs (Specific Inherent Optical Properties) parameters are summarised. The measured range of the a_{TR} slope and of the a_{CDOM} slopes (Figures 2 to 4) are similar to those reported by Bukata et al. (1995) for inland and coastal waters.

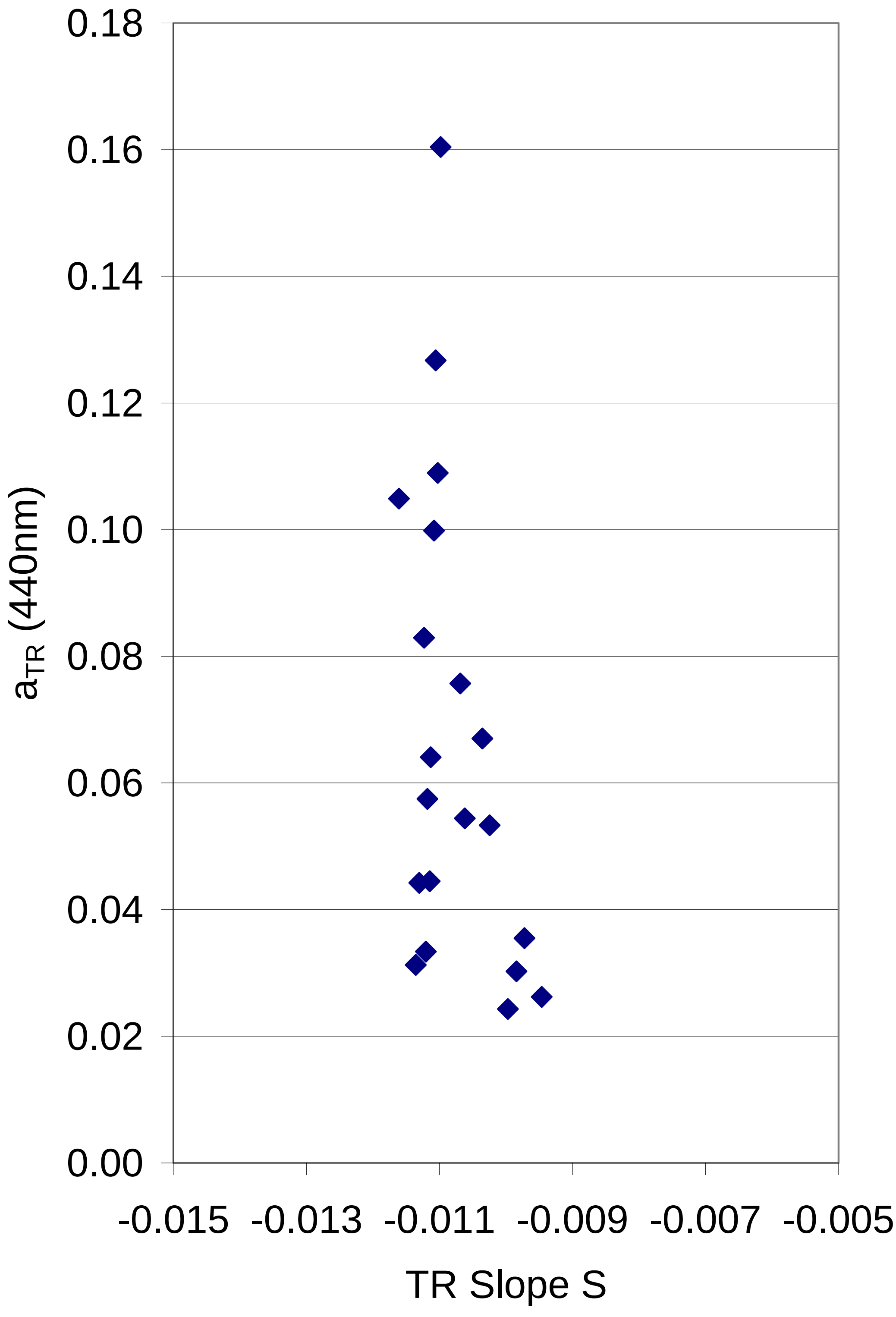


Figure 2. A scatterplot of the optical parameterisation for the tripton absorption: it relates the slope (the colour in terms of hue) to the intensity per concentration unit

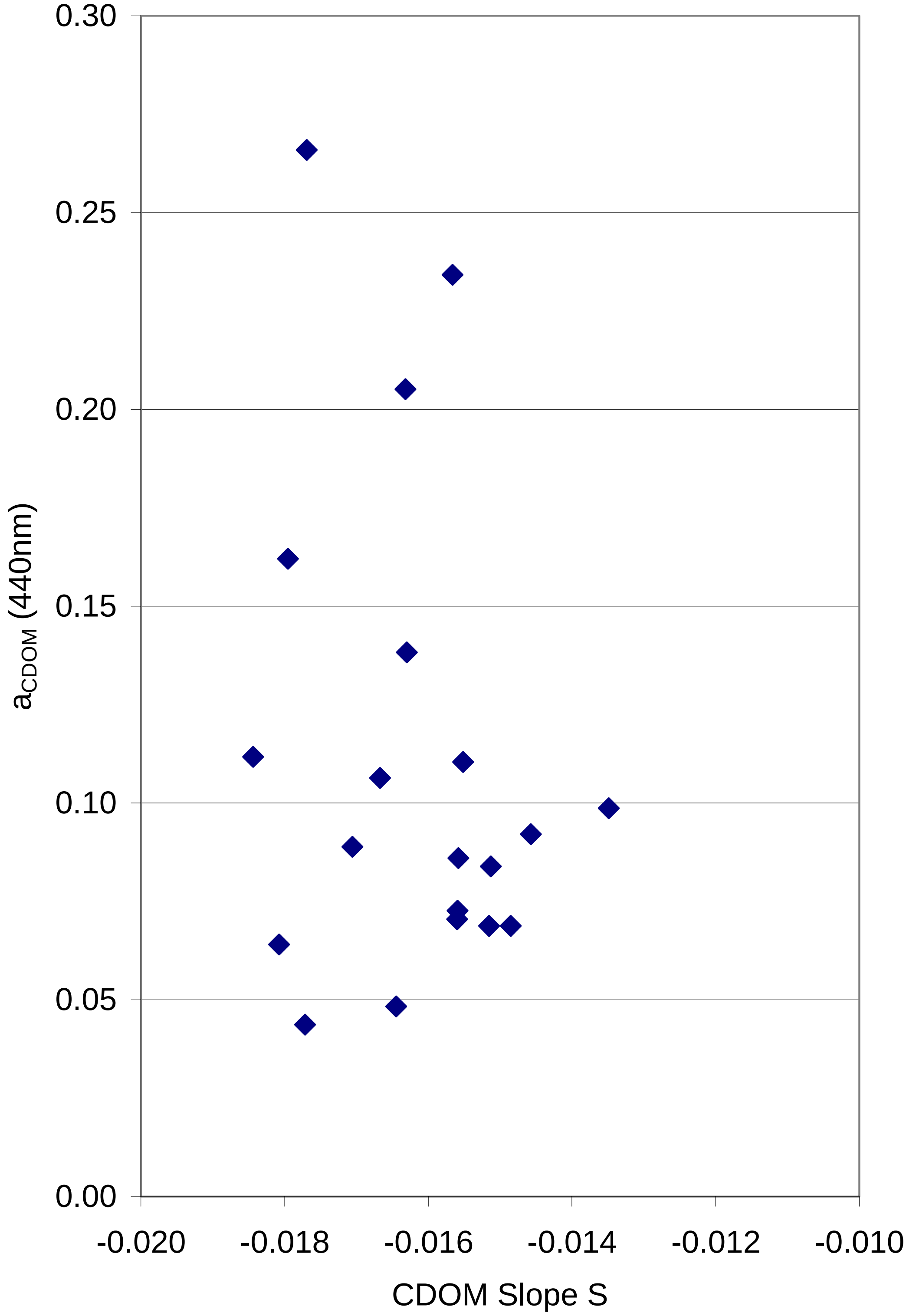


Figure 3. A scatterplot of the optical parameterisations for the CDOM absorption: it relates the slope (the colour in terms of hue) to the intensity of light absorption

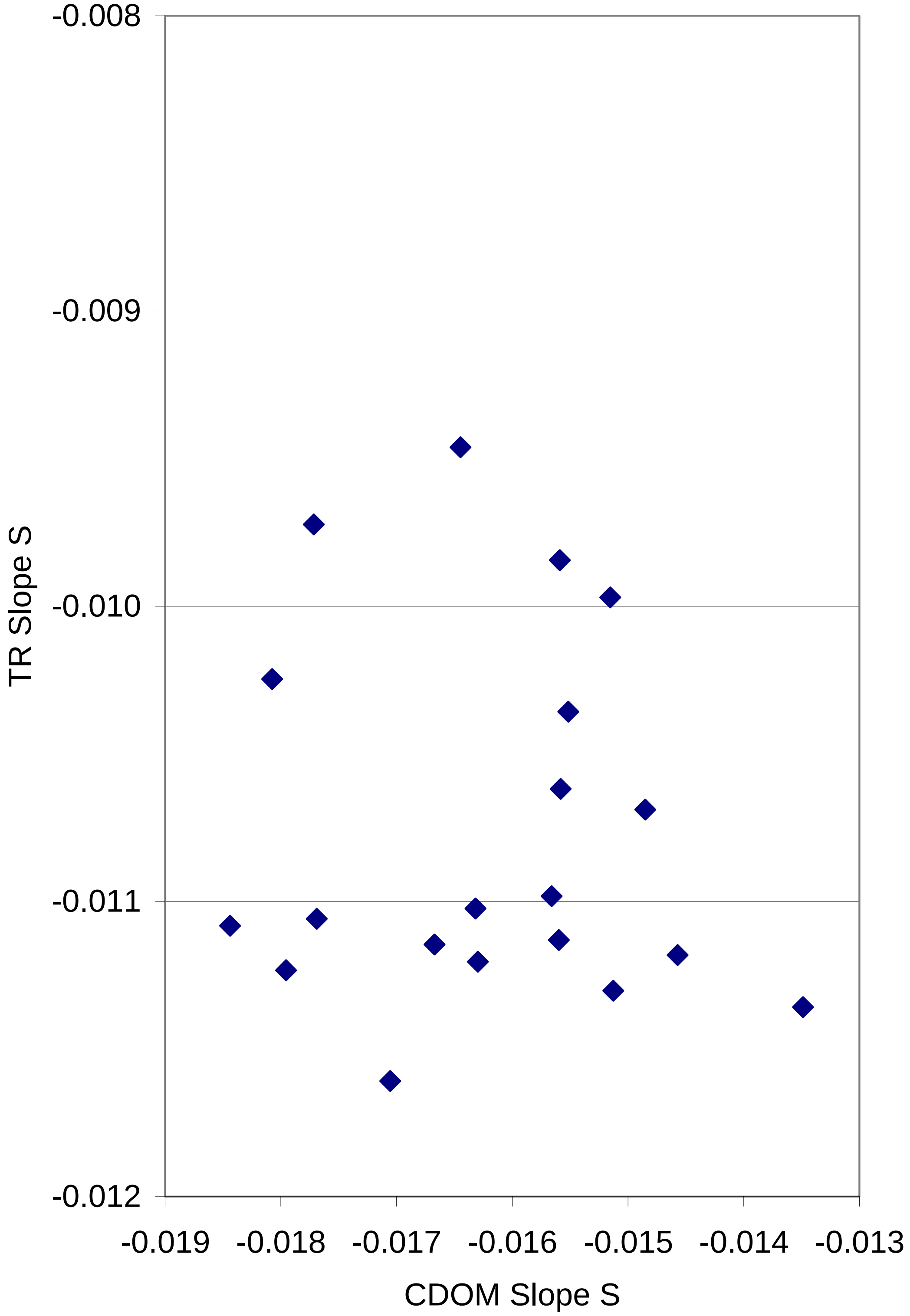


Figure 4. A scatterplot of the two optical parameterisations for the tripton and the CDOM absorption: it relates the slopes (the colour in terms of hue) of these two optically active components

Table 1. Underwater light climate sample site characteristics for the 20 sites sampled in July–August 2004. Station numbers correspond to the sites marked on Figure 7.

Station	Location	Date	Time	Latitude	Longitude	Depth (m)	Secchi (m)	Tide	Cloud	Wind (knots)	Current (knots)
Site 1	South Goat Island	27-Jul-04	10:00	27.52717	153.3878	8.5	5.5	0.4	1-Aug	15-20	NE 5
Site 2A	Rainbow Channel A	27-Jul-04	14:00	27.41518	153.421	19 - 22	6.25	1.1	2-Aug	15-20	NE 6
Site 2B	Rainbow Channel B	27-Jul-04	15:15	27.41521	153.4209	20.5	n/a	1.5	3-Aug	10	NE 7
Site 2C	Rainbow Channel C	28-Jul-04	9:15	27.4149	153.4212	19 - 21	4.5	0.8	5-Aug	5	NE 8
Site 2D	Rainbow Channel D	28-Jul-04	11:00	27.41487	153.4211	19	5.75	0.45	2-Aug	0 - 3	NE 9
Site 3	NW Peel Island	28-Jul-04	14:50	27.46699	153.3267	10	6.25	0.9	2-Aug	n/a	NE 10
Site 4	South Mud Island	29-Jul-04	9:40	27.40016	153.2814	14.5	6	1	5-Aug	1 - 2	NE 11
Site 5	Bramble Bay	29-Jul-04	11:10	27.32306	153.1066	4.4	3.5	0.6	<1/8	1	NE 12
Site 6	Bramble Bay	29-Jul-04	12:05	29.27903	153.0825	1.7	bottom viz	0.4	<1/8	none	NE 13
Site 7	West Bank Bramble Bay	29-Jul-04	13:15	27.34692	153.1519	0.75	bottom viz	0.4	<1/8	1 - 2	NE 14
Site 8	Luggage Point	29-Jul-04	14:25	27.35838	153.1728	7	2.25	0.5	1-Aug	2	NE 15
Site 9	Diabla Passage	30-Jul-04	10:10	27.4685	153.3777	3.5	bottom viz	1.3	3-Aug	8 - 10	NE 16
Site 10	Blue Hole	30-Jul-04	12:30	27.32452	153.3865	4.7	bottom viz	0.4	4-Aug	8 - 10	NE 17
Site 11	Blue Hole Channel	30-Jul-04	14:05	27.3198	153.3818	0.5	bottom viz	0.3	clear	8 - 10	NE 18
Site 12	South Deception Bay	31-Jul-04	9:50	27.18238	153.0809	5	bottom viz	1.6	2-Aug	5 - 10	NE 19
Site 13	Caboolture River Channel	31-Jul-04	11:00	27.15158	153.0586	2.5	bottom viz	1.3	2-Aug	10	NE 20
Site 14	Deception Bay Reference Site	31-Jul-04	11:45	29.12257	153.1658	0	3.75	1	4-Aug	10 - 15	NE 21
Site 15	Tangalooma	31-Jul-04	13:10	27.16496	153.3242	16	4.5	0.4	Clear	5	NE 22
Site 16	North Mud Island	2-Aug-04	9:45	27.26898	153.2485	16.5	4.25	1.8	Clear	2 - 5	NE 23
Site 17	Fishermans Gutter (Moreton Banks)	2-Aug-04	12:15	27.38456	153.3654	3	bottom viz	1.5	1-Aug	1 - 2	NE 24
Site 18	Wanga Wallen Banks – Wallum Pool	2-Aug-04	13:40	27.4262	153.4283	1.5	bottom viz	0.9	1-Aug	5	NE 25
Site 19	The Hook	2-Aug-04	15:20	27.3785	153.3985	2.5	bottom viz	0.4	1-Aug	15 - 20	NE 26
Site 20	Blue Hole	3-Aug-04	11:00	27.32429	153.3864	n/a	n/a	1.8	6-Aug	15 - 20	NE 27

Table 2. Concentration of the organic and inorganic water column constituents for the 20 sites sampled in July–August 2004. Station numbers correspond to the sites marked on Figure 7.

Station	TSS (mg/L)	Chl a (µg/L)	CDOM
Site 1	1	0.53	0.09
Site 2A	3.1	0.71	0.07
Site 2B	2.5	0.51	0.05
Site 2C	2.9	0.90	0.08
Site 2D	0	0.00	0.00
Site 3	2.6	0.39	0.10
Site 4	3	0.46	0.06
Site 5	3.3	2.51	0.11
Site 6	3.6	1.01	0.27
Site 7	2.7	1.00	0.21
Site 8	4.2	2.18	0.23
Site 9	2.8	0.71	0.09
Site 10	2	0.37	0.14
Site 11	n/a	n/a	n/a
Site 12	2.9	0.42	0.11
Site 13	2.9	0.68	0.16
Site 14	2.7	0.68	0.09
Site 15	11.6	0.46	0.04
Site 16	3.3	0.67	0.07
Site 17	2.2	0.41	0.07
Site 18	3.3	0.73	0.11
Site 19	2.4	0.50	0.07
Site 20	n/a	n/a	n/a

Table 3. Parameterisation of the IOPs and SIOPs from the 20 sites sampled in February 2001

	Amity Jetty	North Peel Island	Deception Bay	Shipping Channel	Godwin Beach	North Peel Island	Coffee Pot	Luggage Point	Comlsley Ramp	Logan River entrance	Logan River upstream
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11
$a_{TR\ (slope)}$	n/a	-0.00552	-0.00509	n/a	-0.00228	-0.00623	-0.00449	-0.00862	-0.00677	-0.00817	-0.00919
$a_{TR\ (440)}$	n/a	0.152699	0.116436	n/a	0.088234	0.165598	0.066177	0.355865	0.31117	0.497659	3.405983
$a_{CDOM\ (slope)}$	n/a	n/a	-0.0166	-0.01838	-0.01709	0	-0.01072	-0.01671	-0.01522	-0.01592	-0.01348
$a_{\ CDOM\ (440)}$	n/a	n/a	0.384409	0.127836	0.746133	0	0.187399	0.897518	1.278652	1.353035	1.452689
$bb\_{_{p@542\ nm}}$	0.004178	0.023953	0.024354	0.00615	n/a	0.022442	0.045834	0.054778	0.07534	0.31012	0.126663
Gamma	0.527566	0.679453	0.483658	0.457942	n/a	0.747479	0.696192	0.518721	0.434688	0.22	0.229616
bb_{TR}	0.004161	0.023138	0.023388	0.005721	n/a	0.022442	0.044102	0.05136	0.074244	0.30023	0.125879
a_{TR}^*	n/a	0.037079	0.105433	n/a	0.049806	0.039329	0.035293	0.135554	0.061491	0.081282	0.106435
bb_{TR}^*	0.000682	0.005619	0.021177	0.008346	n/a	0.00533	0.02352	0.019564	0.014671	0.049036	0.003934
bb_{ph}^*	4.77E-05	0.000393	0.001482	0.000584	n/a	0.000373	0.001646	0.001369	0.001027	0.003433	0.000275
TSS (mg/L)	6.125	4.263158	1.15	0.736842	1.777778	4.210526	1.948718	2.8	5.135135	6.324324	32.2
Chl-Ǔ (µg/L)	0.348157	2.071273	0.651886	0.734603	0.089	n.d.	1.051818	2.496238	1.066959	2.881282	2.848
Phy_{DW}	0.024371	0.144989	0.045632	0.051422	0.00623	0	0.073627	0.174737	0.074687	0.20169	0.19936
Tr_{DW}	6.100629	4.118169	1.104368	0.68542	1.771548	4.210526	1.875091	2.625263	5.060448	6.122635	32.00064

4.1.6 Analysis and presentation of field survey data

To enable the integration of all field data sets with airborne and satellite images and their derived map products, extensive data cleaning and pre-processing was carried out. All field survey data sets with benthic cover information, including substrate cover type, seagrass species, seagrass density and above-ground seagrass biomass, were attached to a set coordinates determined by their sampled location in the field and a corresponding GPS measurement. As a result, all data were assigned to an individual sample point, even though the measurements of some of them, e.g. benthic cover transects on the Eastern Banks, were derived from analysis of individual photographs. The data associated with each type of information collected was attached to a survey point, then stored as an individual data layer (shapefile) within the ArcView GIS software. This enabled the field survey data sets from each collaborating organisation to be checked and integrated. A map showing the spatial variation in each surveyed variable could then be generated for the area surveyed (Figures 5 and 6). These data could then be overlaid on the image data sets and their derived maps for calibration and validation of mapping algorithms.

The photo transects completed on the Eastern Banks by the CRC survey team represent one of the most comprehensive sets of georeferenced data for seagrass beds collected in Australia and globally. The individual photo or aggregated transect data can be used to calibrate and validate image-based maps over a range of sensor spatial resolutions.

Figure 8 shows the level of detail present in each fully processed transect survey. Each sample point, at 2.0 m intervals, contains information within each photo-point of species composition and horizontal projective foliage cover or density. Above-ground biomass was measured from the two biomass core sample sites shown as squares in Figure 8. We have refined this approach through our coral reef survey work and through this project have established an operational technique to collect survey information in aquatic and terrestrial environments. Most importantly, the scale of data collection, georeferencing and data storage associated with this method makes it highly suited for airborne and satellite image data of high to moderate spatial resolutions. We have developed a standard field survey method and are now working with other agencies, such as the Great Barrier Reef Marine Park Authority, Australian Institute of Marine Science, World Bank Global Environment Facility programs and various management agencies in the south-west Pacific to have it applied widely. This method enables collection of standard monitoring data in a format that can be used with remotely sensed data for mapping and monitoring.

Figure 5. Moreton Bay—2004 field survey components showing the extent of data collected by each component of the field survey team

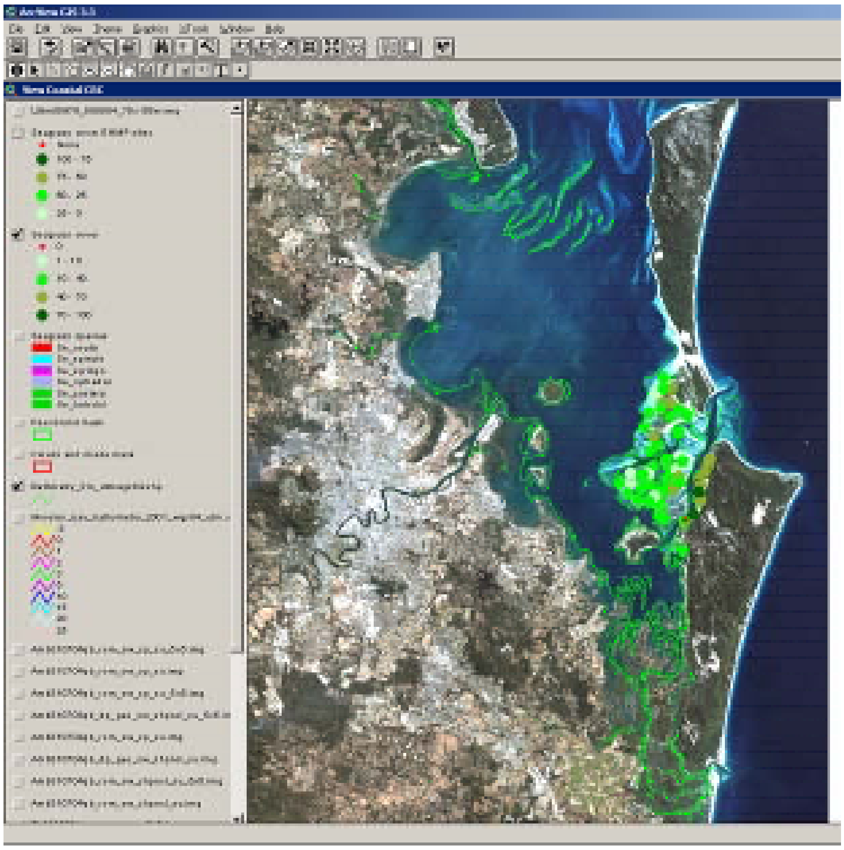


Figure 6. Example of the ArcView GIS used to store and manipulate all image and field data sets collected for the project

Figure 7. Sites sampled for inherent and apparent optical properties by the CSIRO–UQ field team in July 2004

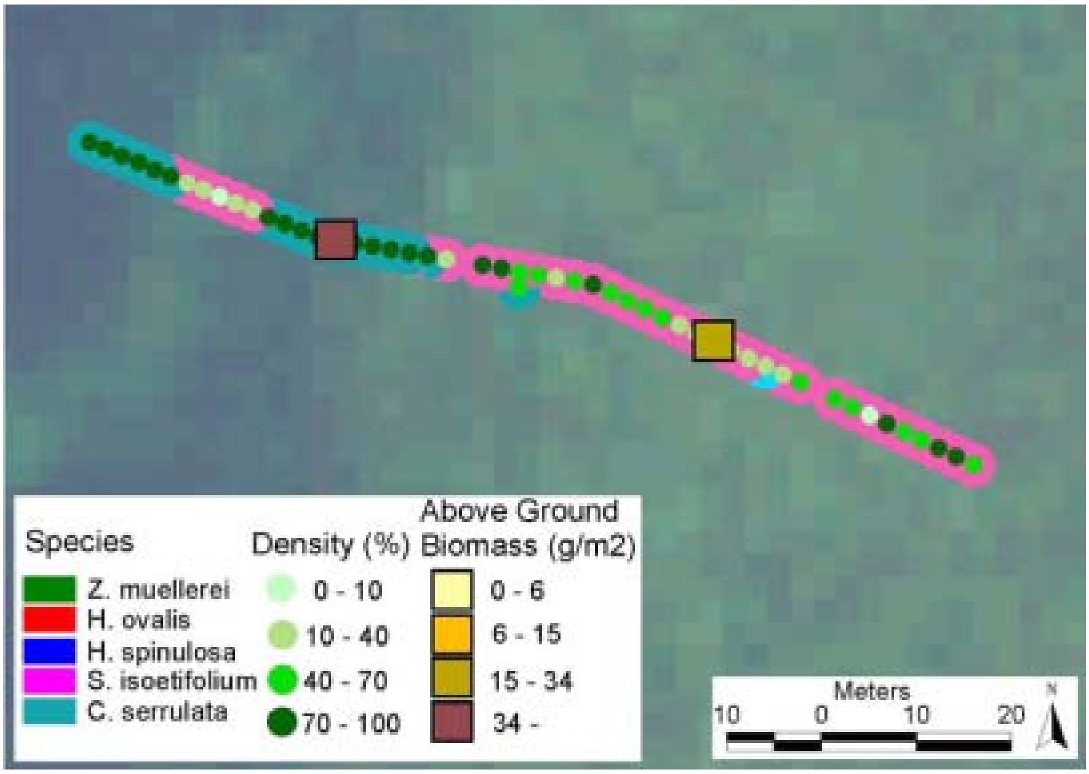


Figure 8. Example of the fully processed and georeferenced field data sets overlaid on a true-colour subset of the Quickbird-2 image (2.4 m pixels) for one of the 100 m-long field transects. Note that only two biomass cores were collected along each transect.

4.2 Image acquisition and processing

4.2.1 Image acquisition

Four types of image data were collected to represent the current range of commercially available image data sets that could be used for mapping seagrass properties and other benthic parameters (depth, water quality) types in coastal waterways with relatively clear waterbodies. Table 4 lists the four data sets, along with the times of acquisition and the differences between the type of information captured. Figure 9 demonstrates the extent of each image coverage overlaid on the Landsat 5 TM image base. The aim of the project was to capture all of the image data at the same time as the field data so that the maps derived from the image data for seagrass, bathymetry and water quality could be checked against coincident field data. However, the realties of satellite orbit cycles, tidal cycles, cloud cover, smoke from fires on North Stradbroke Island and personnel only allowed a partial match-up. The match from field and image data (28–31 July 2004) was made for the airborne hyperspectral (CASI-2) and high spatial resolution satellite multispectral (Quickbird-2) data sets. Due to the 16-day repeat cycle of Landsat 5 TM, the next cloud-free coverage was obtained on 8 August, eight days after field sampling was completed. Aerial photography acquisition (1–15 September) was controlled by the POBC, and outside our control. The Quickbird-2, Landsat 5 TM and aerial photography data sets represent the most commonly used and commercially available data sets for mapping benthic cover properties in coastal environments. The CASI-2 sensor data were included as they represent the optimal sensor for this type of mapping and provide the necessary data for the most accurate and detailed mapping algorithm developed by the CSIRO team.

Table 4. Summary of image data set collection parameters for CASI-2, Quickbird-2, Landsat 5 TM and aerial photography data used in the project

	Sensor and data type			
Image attribute	CASI -2	Quickbird-2	Landsat 5 TM	Aerial Photography
Date acquired	28 July 2004 29 July 2004	31 July 2004 17 September 2004	9 August 2004	September 2004
Time acquired	1100–1300 on 28 July 1100–1300 on 29 July	0956 hrs 0950 hrs	0945 hrs	n/a
Tidal stage	+/- 1 hour of low tide 0.37 m at 1200 hrs 0.31 m at 1303 hrs	59 min after a 1.7 m high tide 1.74 m at 0859 hrs 1 hr 20 min before a 1.9 m high tide 1.9 m at 1107 hrs	Low tide acquisition 0.57 m at 0947 hrs	Low tide acquisition
Pixel size	4 m x 4 m	2.4 m x 2.4 m	30 m x 30 m	n/a
Image extent	Eastern Banks Port of Brisbane–Fisherman–Whyte Islands	Eastern Banks	Moreton Bay Caloundra to mid-point of South Stradbroke Island	Port of Brisbane–Fisherman–Whyte Islands
Spectral bands used for mapping in water	16 Airborne hyperspectral	4 Satellite multispectral	4 Satellite multispectral	Airborne analogue

Figure 9. Extent of images captured for the project during the July–September period, 2004. The Landsat 5 TM data were collected for the entire Moreton Bay region. The green rectangle represents Quickbird-2 (July and September), yellow rectangles represent the CASI-2 airborne hyperspectral data (28–31 July 2004) and the pink rectangle represents the Port of Brisbane Corporation's digital aerial photography (1–15 September 2004).

Figure 10. Example of the spatial resolution differences for the image data sets collected over a 1.5 km x 1.5 km area of the Wanga Wallen Banks. From left to right: Landsat 5 TM (30 m), CASI-2 (4 m) and Quickbird-2 (2.4 m).

4.2.2 Image corrections and pre-processing

Image corrections and pre-processing were necessary to bring each data set into a format that could be integrated with other images and the field survey data sets.

Image corrections involved both geometric and radiometric operations, to match the images to existing spatial data held by government agencies and to remove atmospheric contamination. Both the Quickbird-2 and Landsat 5 TM data were georeferenced to field survey points from distinctive features on the Eastern Banks. In both cases the data were delivered in a format with some error in georeferencing, with the Quickbird-2 data being ± 24 m or 10 pixels out. Using the field data points ensured that our image and field data sets matched as closely as possible. The CASI-2 data were meant to be georeferenced by the data provider, but due to problems with the data collection this was not possible. Manual adjustment and matching of each flightline, and then georeferencing to Quickbird-2 and Landsat TM image data, was conducted. The aerial photographs were orthorectified and mosaiced manually.

Radiometric corrections involved reduction of atmospheric and air–water interface attenuation effects. The purpose of these corrections were to maximise the radiance signal leaving the water, which contains information about water depth, water column constituents and the reflectance properties of substrate cover types. This was done for the Quickbird-2, CASI-2 and Landsat 5 TM image data sets to isolate the subsurface irradiance reflectance signal (R0-). The procedure used to conduct this correction is described in detail by Brando and Dekker (2001) and Phinn et al. (2003). Additional corrections were applied to the

CASI data set due to its acquisition geometry to remove cross-track illumination effects and other radiometric inconsistencies.

As past work by the project team on mapping seagrass properties in Moreton Bay had established from simulation models and field verification that multispectral image data could only be used to map substrate cover properties to a depth of 3.0 m, a mask was applied to the Quickbird-2 and Landsat 5 TM images to exclude areas deeper than 3.0 m from the mapping process. This was done to constrain the mapping on the Eastern Banks. For the remainder of Moreton Bay, mapping from the Landsat 5 TM image was confined to exposed inter-tidal areas, as the image was captured at low tide. All other areas with seagrass cover, which were either too deep or turbid were sampled by the EPA–EHMP field survey team and a map was derived from those data. Finally, in both the Quickbird-2 and CASI-2 images there were a number of clouds that obscured the Bay. These areas were manually digitised and masked out from further analyses.

Figure 11. Image mask outlines overlaid on the August 2004 image. Yellow = 3.0 m AHD bathymetric contour. The mask was used to exclude select areas for image processing operations.

4.2.3 Seagrass mapping—Eastern Banks

Seagrass maps (showing seagrass density, species composition and above-ground dry biomass) were created from field data and corrected image data sets, Quickbird-2, Landsat 5 TM and CASI-2. For this process the field data were divided into two sets, one for calibration and one for validation. The division was based on an equal distribution of sites over each of the four major areas that make up the Eastern Banks: Wanga Wallen Banks, Amity Banks, Maroon Banks and Moreton Banks (Figure 11). The very high spectral and radiometric resolutions of the CASI-2 data enabled it to be subject to an additional and more complex processing algorithm to map water depth, seagrass density and water column constituents. This is discussed in more detail in Section 4.2.5.

Seagrass density

The following process describes the methods applied to derive seagrass density from each of the fully corrected Quickbird-2, Landsat 5 TM and CASI-2 image data sets, with areas deeper than 3.0 m masked out. In this context 'seagrass density' refers to the horizontally projected foliage cover of the seagrass, i.e. the amount of substrate covered by seagrass when viewed from directly above. The methods used to convert the images to maps were supervised classification and regression models.

Supervised classification approach

The GPS-referenced seagrass density field data collected close to the date(s) of each image acquisition were used as training areas for the image classification process. Reflectance signatures were extracted from each of the remotely sensed images for field survey locations of known seagrass density, enabling a characteristic 'spectral reflectance signature' to be defined for four levels of seagrass density. Each image pixel was then subject to a minimum-distance-to-means algorithm to group pixels with similar reflectance signatures. This process enabled each pixel to be assigned a label of either sand, water body > 3m, or seagrass cover (1–10%, 10–40%, 40–70% and 70–100%).

Regression analysis approach

For each field calibration site (transect photograph every 2.0 m) with a measured seagrass density value, the corresponding pixel reflectance signature was extracted from the image. A regression analysis was applied to the seagrass density and the reflectance values. The regression model with greatest coefficient of determination (r^2) was selected after experimentation with varying band combinations. The resultant regression function was then applied to each pixel in the image to estimate seagrass density. This produced a continuous and quantitative map of seagrass density, as opposed to the categorical map produced from the classification approach.

Seagrass species composition

The following process describes the method used to map seagrass species composition from the fully corrected Quickbird-2 and CASI-2 image data on the Eastern Banks. The mapping was confined to areas of seagrass habitat, hence no other substrate cover types were considered. Landsat 5 TM data were not subject to this processing as the pixel size and radiometric resolution were insufficient to detect species level differences.

The procedure used is the same as the supervised classification applied to create seagrass density maps described above. However, for the species composition maps, the GPS referenced seagrass species composition estimates from each photo along the survey transects was used as a training site for the image classification process. This process enabled each pixel to be assigned a label of either: sand, water > 3 m, *Halophila ovalis*, *Halophila decipiens*, *Halophila spinulosa*, *Halodule uninervis*, *Zostera muellerei*, *Cymodocea serrulata or Syringodium isoetifolium* and several common occurring combinations of these species.

Seagrass biomass

To create a map of above-ground dry seagrass biomass, a regression analysis was applied to the biomass estimates made from the field samples and fully corrected Quickbird-2, Landsat 5 TM and CASI-2 images. A similar approach was applied as with the seagrass density, i.e. variations in band combination and selection of the model with greatest coefficient of determination (r^2). This is the same approach as described above, but in this case pixel values were compared with the two field samples taken along each transect. This resulted in a regression function that was applied to each of the image data sets. The resultant regression function was then applied to each pixel in the image. This produced a continuous and quantitative map of above-ground dry-weight seagrass biomass.

4.2.4 Seagrass mapping—Moreton Bay

In a collaborative effort between the EHMP and UQ teams, a seagrass density map for all of Moreton Bay was created by integrating image and field survey data. The image-based seagrass density maps outlined above were combined with field survey data to produce a seagrass density map with four density classes (1–25%, 25–50%, 50–75% and 75–100%), based on previous surveys by the EHMP team.

As discussed in the preceding sections, the field data were collected using different survey methods and by each organisations for the regions around Moreton Bay, which ranged from shallow and clear waters (Eastern Banks) to turbid shallow (western Bay) and turbid deep waters (western Bay and river mouth areas). The Bay-wide map combines seagrass maps derived from remote sensing (for the clear shallow water and the exposed inter-tidal seagrass beds) and manually digitised maps (for the deep and or turbid waters) from point-based field survey.

The remote sensing input was the seagrass density type map produced from the Landsat 5 TM data described above for the Eastern Banks and exposed intertidal areas throughout the Bay. The output maps were transformed to polygons for the exposed and clear shallow regions of the Moreton Bay. The field survey map used was based on data from spot-checks using a drop camera and observers. These data were interpreted in relation to a bathymetric surface and Landsat 5 TM image to draw polygon boundaries around seagrass density classes.

The field and remote sensing based polygons were joined together and inspected for consistency by C. Roelfsema and S. Phinn (UQ) and N. Udy (QPWS). Where there was overlap in area covered between the two data sets, the remote sensing based mapping was used, as it provides a continual coverage of the area as opposed to the point-based survey data. Additional information was also added to each polygon corresponding to zones of known seagrass density to indicate the dominant species composition. This was done based on field data and expert field knowledge.

4.2.5 Integrated depth, water quality and seagrass mapping

The mapping of depth, water quality and seagrass coverage using CASI-2 airborne hyperspectral data required a physics-based mapping approach as implemented by the CSIRO Environmental Remote Sensing group (Phinn et al. 2004).

At the core of the physics-based method, we chose to implement a modified version of the semi-analytical model and optimisation approach originally developed by Lee at al. (1999), dubbed SAMBUCA (Semi-Analytical Model for Bathymetry, Un-mixing, and Concentration Assessment).

SAMBUCA

The essence of the approach lies in expressing the measured remote sensing reflectance $r_{rs}^{measured}$ (obtained from each pixel in a remote sensing image) as a function of a set of simple variables. This modelled remote sensing reflectance, $r_{rs}^{modelled}$, is then compared to $r_{rs}^{measured}$ using a goodness-of-fit or, error function. The set of variables that minimises the difference between these two spectra is retained as the result of the minimisation. These variables are then used to estimate the environmental variables being sought, e.g. water column depth. Taking the work reported here as an example, SAMBUCA estimates the concentrations of optically active constituents in the water column (chlorophyll, CDOM and tripton), water column depth, and benthic substrate composition that produces the best fit between modelled and measured $r_{rs.}$ These five environmental parameters are solved for on a pixel-by-pixel basis.

The complete model parameterisation is given below.

$$r_{rs}(\lambda)_{\text{mod}\,elled} = f\left(C_{CHL}, C_{CDOM}, C_{TR}, X_{PHY}, X_{TR}, q1, H, S_C, S_{TR}, a^*_{\text{TR}}(\lambda_0), Y\right) \qquad (1)$$

Where:

- C_{CHL} is the concentration of chlorophyll-Ŭ
- C_{CDOM} is the concentration of CDOM where a*CDOM (550) is set to 1
- C_{TR} is the concentration of tripton
- X_{PHY} is the specific backscattering due to phytoplankton
- X_{TR} is the specific backscattering due to tripton
- q1 is the ratio of substrate 1 to substrate 2 within each pixel
- H is the water column depth
- S_C is the slope of the CDOM absorption
- S_{TR} is the slope of tripton absorption
- $a^*_{TR\,(550)}$ is specific absorption of tripton at 550 nm, which is sample dependent
- Y is the slope of the backscattering of both tripton and phytoplankton.

Note that the set of environmental parameters for which SAMBUCA solves can be confined, and that SAMBUCA typically solves for water column depth, substrate composition and the concentrations of chlorophyll, CDOM, tripton. The remaining variables are determined through field work and laboratory analysis.

The algorithm has been modified to account for more than one substrate cover type. For the work presented here, we allowed for the presence of two substrates within each pixel to limit the processing time. The relative composition of each substrate is determined by the variable q1, described above. SAMBUCA cycles through a given spectral library, retaining the two substrates that allow for the best spectral fit. Each inverted variable, as well as the substrate combination, can be output in a variety of map formats.

SAMBUCA also provides a measure of the goodness-of-fit, between the measured and modelled spectra. In other words, each set of retrieved environmental variables is assigned a confidence rating based on SAMBUCA's ability to model a given subsurface reflectance spectra. The goodness-of-fit can be estimated according to either a spectral albedo matching function or spectral shape matching function, referred to as 'f_val' or 'alpha_val', respectively. For the results reported in this study, a product of f_val and alpha_val was used to assess the spectral match.

Additional output includes an indication of optically deep/optically shallow waters based on the difference between the modelled spectrum using an optically deep system and the modelled spectrum as generated by SAMBUCA.

SAMBUCA can also be used in simulation mode, applicable to for example feasibility studies. The model can be run in 'forward' mode in order to generate a set of modelled spectra. For a given set of simulations, one or more variables can be varied, and the effect on modelled can be evaluated. As an example, using a fixed set of concentrations and SIOPs, modelled spectra can be calculated for several substrate compositions through a range of water depths. The resulting subsurface remote sensing reflectance spectra can then used to evaluate the ability of various remote sensors to detect these changes in substrate composition at different water depths.

The parameterisation of SAMBUCA

Based on the field data described in Section 4.1.5, optical domains were defined for SAMBUCA for the different regions in Moreton Bay. The final optical domain parameterisation is outlined in Table 5.

SAMBUCA was configured to invert for chlorophyll, CDOM, and tripton concentrations, as well as depth and substrate composition. The remaining six variables, S_C, S_{TR}, a^*_{TR} (440), X_{PHY}, X_{TR}, and Y were fixed based on measurements from the July 2004 fieldwork.

Table 5. SAMBUCA parameterisation for the different regions in Moreton Bay

Region:	CHL	CDOM	TR	S_C	S_{TR}	$a^*_{TR}(440)$	X_{PHY}	X_{TR}	Y
Rainbow Channel	0.7	0.07	2.8	0.0157	0.0106	0.0048	0.00038	0.0054	0.681
Brisbane River	1.5	0.2	2.8	0.163	0.01102	0.0041	0.00032	0.010	0.817
Eastern Banks	0.7	0.08	2.8	0.0157	0.0106	0.0048	0.00038	0.0054	0.681

Benthic substrate reflectance libraries

SAMBUCA results are highly sensitive to the substrate reflectance spectral library used as input. The resulting substrate maps estimated by SAMBUCA are restricted by the choice of input substrate spectra. In addition, if a benthic substratum is not represented in the library, SAMBUCA may compensate with the concentrations in the water column, depth, and/or approximate the benthic substratum reflectance with a mixture of other spectra (not necessarily ecologically related) present in the library. The latter effect, caused by spectral ambiguities in the data, can be minimised by an optimally designed substrate reflectance library. For this study, the results from using two different libraries collected in Moreton Bay were investigated.

SAMBUCA's spectral library was initially comprised of averaged spectra for a set of broad, representative substrate cover type classes. These radiance–reflectance signatures were collected in situ, covering as many of the substrate types from Moreton Bay as possible. Because the pixel by pixel inversion with 12 classes is computationally intensive (~half a second per pixel, equating to 40 days for the mosaic of the eastern portion of Amity Banks), we run SAMBUCA with only two substrates (Figure 13) to reduce the processing time for the retrieval of the bathymetry.

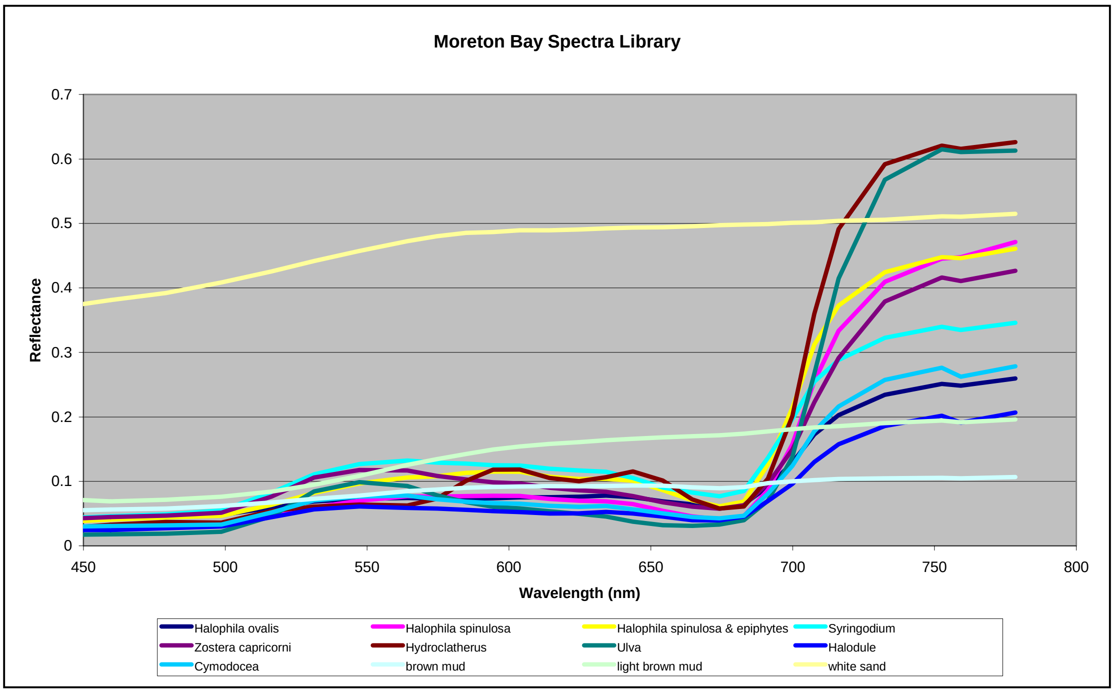


Figure 12. Spectral library of representative benthic substrate cover type classes for Moreton Bay

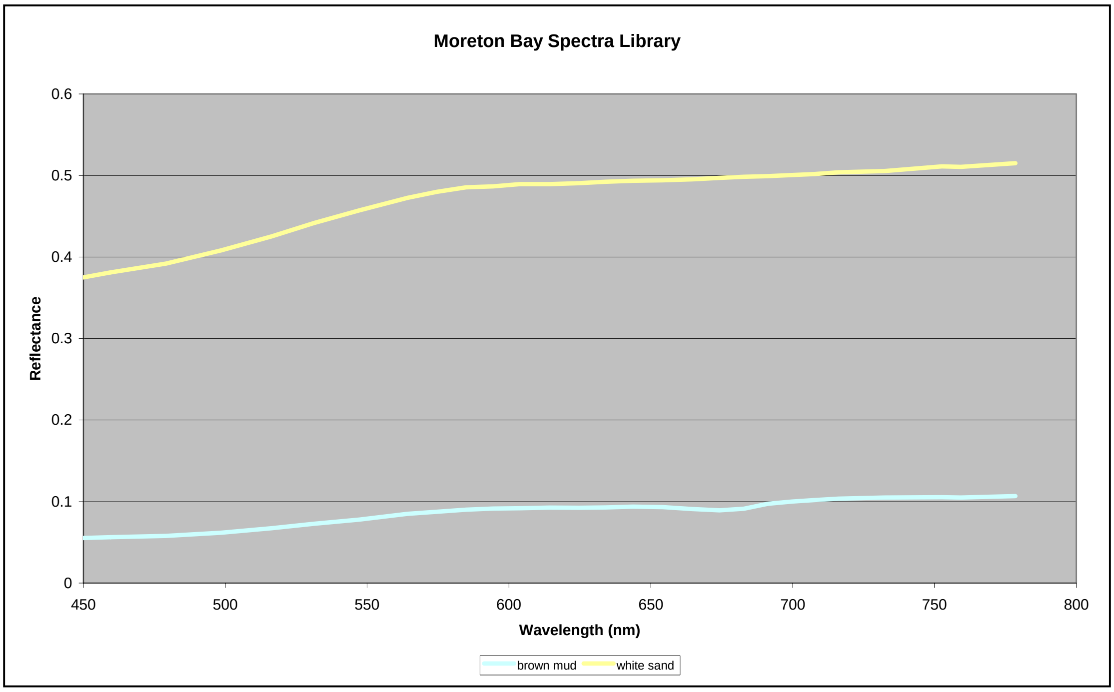


Figure 13. Spectral library of two substrate cover type classes for fast bathymetry retrieval

4.2.6 Error and accuracy assessment

Two main types of accuracy assessments were conducted: (1) using the training or calibration data (pseudo 'error matrix'); and (2) based on validation data. In each case the reported accuracy levels should be interpreted at an individual pixel level, as the probability that the pixel is correctly labelled. For example, an overall accuracy of 75% means that for each pixel the probability it is correctly labelled is 75%, with a 25% probability that it was mislabelled. The individual class accuracy levels are interpreted in a similar manner, i.e. an individual class accuracy of 85% means that for each pixel in that class the probability it is correctly labelled is 85%, with a 15% probability that it was mislabelled.

(1) Training or calibration data—Once each seagrass percent cover and species composition map had been produced, the training sites used in the mapping process were reclassified. The resulting 'pseudo' error matrix was used to quantify the level of agreement between the substrate types identified from the image classification and the field survey data. The 'pseudo' label is applied to this process, as a true reference set would have consisted of independently selected sites where seagrass cover had been measured and not used to train

the image classification process. Hence, the error matrix is only a measure of how well the classification identified the training data, not the whole study area. In this context, individual class accuracy is the level of agreement, expressed as a percentage between the classified substrate map and the reference or training sites. This is commonly expressed as the probability that a classified image pixel actually represents that category on the ground, e.g. a direct match between a pixel assigned to the seagrass cover, class and the field data value at that site.

(2) Validation data—The field data that was not used to create the different maps was used to determine the accuracy of the maps. For each of the field data sites the corresponding map value was extracted from the final maps. Overall accuracy and kappa accuracy were then calculated.

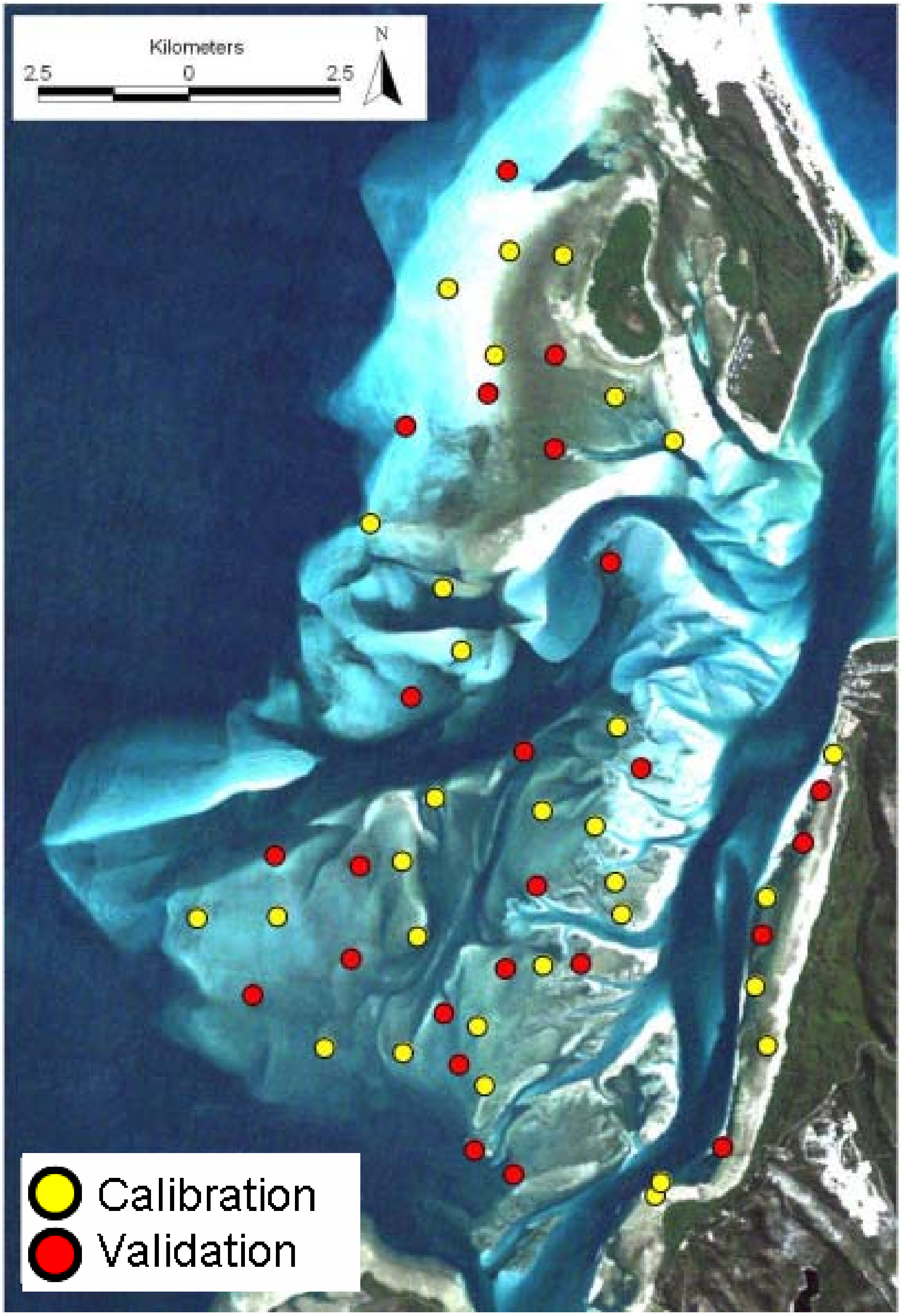


Figure 14. Field sample sites on the Eastern Banks used for training or calibrating the image mapping algorithms (yellow) and validating the resultant maps (red)

5 Results and discussion

5.1 Exploratory analysis of seagrass field survey data

The field survey data set jointly collected by UQ, CSIRO and the EHMP/Marine Parks groups represent a unique data set in itself. The full analysis of these data will allow investigation of seagrass density, biomass and species composition variations across Moreton Bay. For this project we have provided a brief summary of the main trends observed from the data, mainly in the Eastern Banks region. The individual photo and sample point data will be used to support the error and accuracy assessment results, which are reported in a following section.

Seagrass density

Figure 15 depicts the spatial variation in seagrass cover per 100 m-long photo transect on the Eastern Banks and western shores of North Stradbroke and Moreton Islands. Several patterns are evident, with lower cover (< 40%) transects dominating the shallow western section of all of the banks. The highest density or cover areas were found in the more sheltered areas of Wanga Wallen Banks and the bank immediately west of Crab Island at the southern tip of Moreton Island.

Seagrass species composition

Five zones with internally consistent seagrass species assemblages were evident from visual assessment of the transect-level seagrass species composition data (Figure 16). The zones observed were:

(1) high cover on the Wanga Wallen Banks, with mono-specific zones of *Zostera* sp., *Cymodocea* sp. and *Halophila syringodium*

(2) low to medium cover on the eastern section of Eastern Banks with a mix of *Zostera* sp. and *Halophila ovalis*

(3) the western section of the Eastern Banks dominated by low cover mixed species assemblage of *Halophila spinulosa* and *Halophila ovalis*

(4) the bank immediately south-west of Crab Island, dominated by high cover of *Zostera* sp.

(5) the western section of the previous zone, consisting of low to medium cover with mixtures of *Halodule* sp., *Halophila ovalis* and *Halophila syringodium.*

Seagrass above-ground biomass

A similar spatial pattern to variations in density (Figure 15) was evident in the distribution of above-ground biomass on the Eastern Banks (Figure 17). The

Wanga Wallen Banks area and area immediately to the south-west of Crab Island had the highest levels, with lower levels across the shallower areas on the Eastern Banks.

Transect details

Figure 18 illustrates the level of detail available at the scale of individual photo analysis points in each of the 56 m x 100 m-long transects completed on the Eastern Banks. At the most general level, substrate cover types are presented for each photo-point. This summary was produced by aggregating all of the seagrass species cover data within each photo to an individual seagrass cover measure. The seagrass species composition can then be presented separately for each photo-point (lower graph in Figure 18). These data can be obtained by request from the authors for all 56 transects.

Seagrass depth associations

As depth information was also calculated for each transect, it was possible to assign a depth value to each photo-point and then investigate the pattern of seagrass–depth distribution across different seagrass species (Figures 19 and 20). These plots were used to derive species–depth association rules to guide several of the image based mapping approaches. The species–depth association rules adopted are reported in Table 6.

Table 6. Species–depth association rules adopted in the SAMBUCA inversion. The data sources are: MB_Aug04—spectra measured with the CSIRO Ramses during the July–August 2004 fieldwork; UQ_ASD—spectra measured by C. Roelfsema with the UQ ASD Fieldspec from 2001–2004 fieldwork.

Substrate	Min depth	Max depth	Spectra name	Data source
Halophila ovalis	0	5	Halophila ovalis_Site 20	MB_Aug04
Halophila spinulosa	0	15	Halophilia spinulosa_Site 11	MB_Aug04
Halophila spinulosa and epiphytes	0	15	Halophila spinulosa & epiphytes_Site 11	MB_Aug04
Syringodium isoetifolium	0	3	Syringodium_Site 20	MB_Aug04
Zostera muelleri	0	5	Zostera_Site 20	MB_Aug04
Hydroclatherus	0	10	Hydroclatherus_Site 7A	MB_Aug04
Ulva	0	10	Ulva_Site 7A	MB_Aug04
Halodule uninervis	0	5	Halodule univervis	UQ_ASD
Cymodocea serrulata	0	3	Cymodocea serrulata	UQ_ASD
Brown mud	0	25	Brown mud	UQ_ASD
Light brown mud	0	25	Light brown mud	UQ_ASD
White sand	0	25	White sand	UQ_ASD

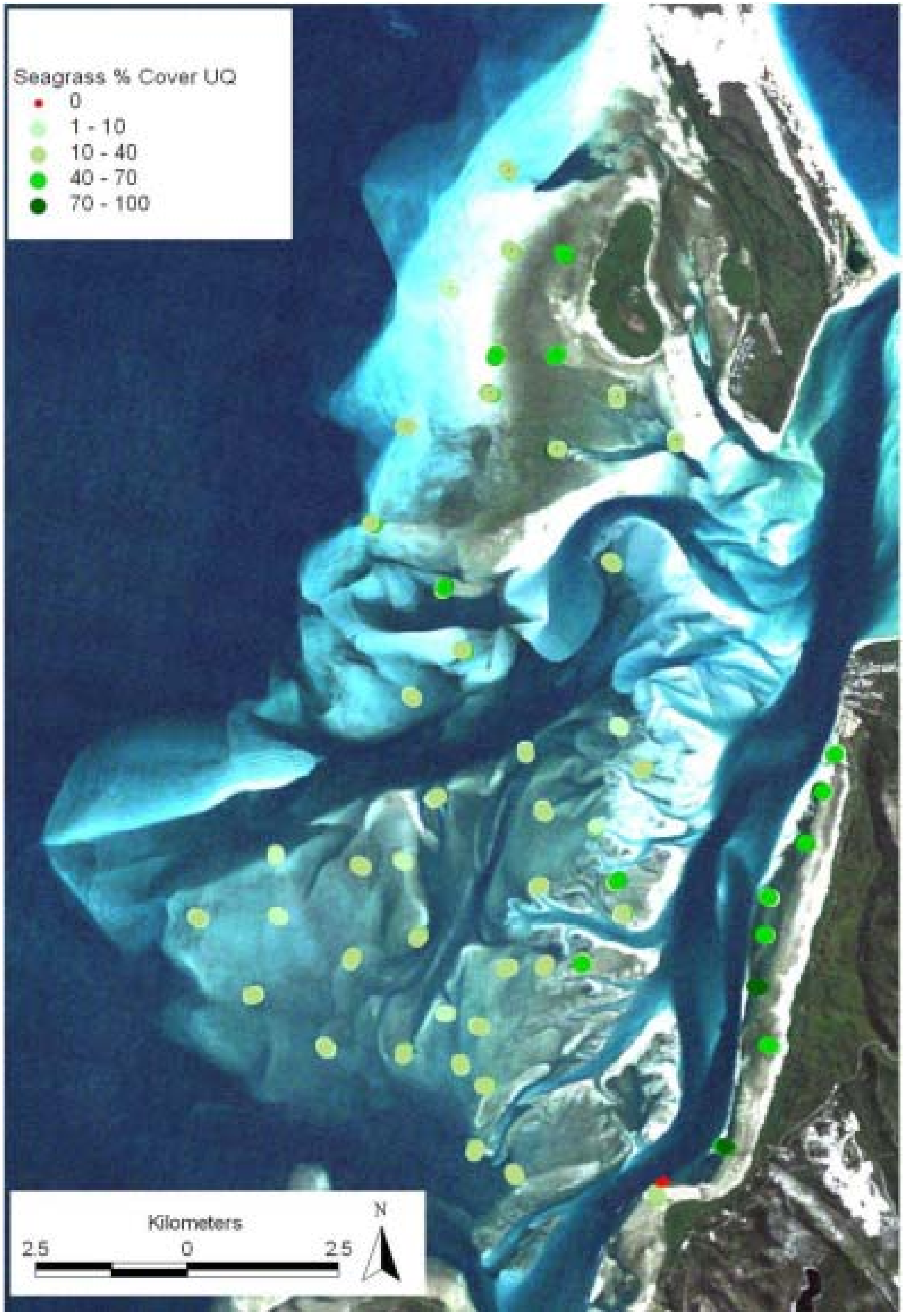


Figure 15. Transect-level summaries for field survey of seagrass density, collected from Eastern Banks in July 2004

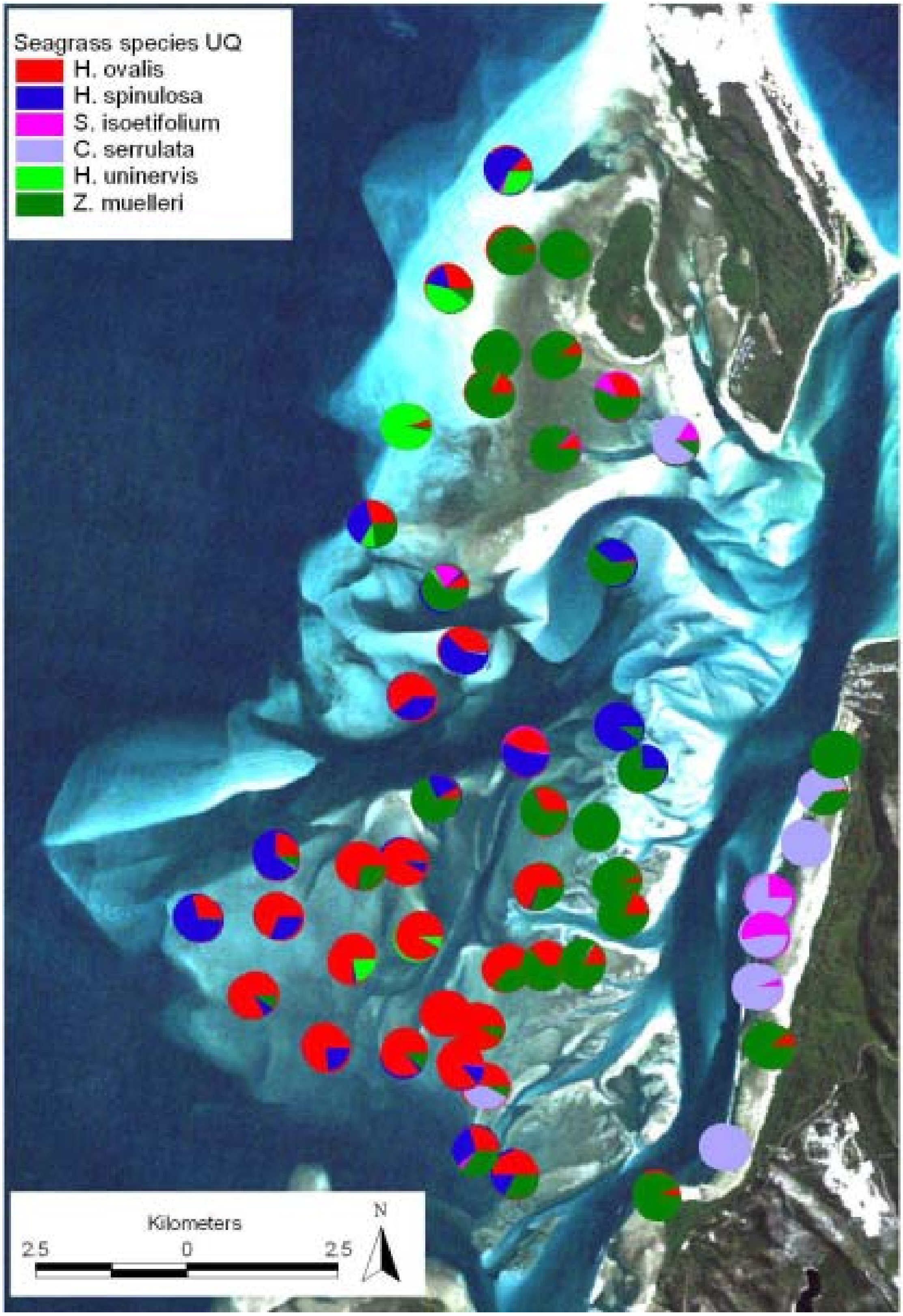


Figure 16. Transect-level summaries for field survey of seagrass species composition, collected from Eastern Banks in July 2004

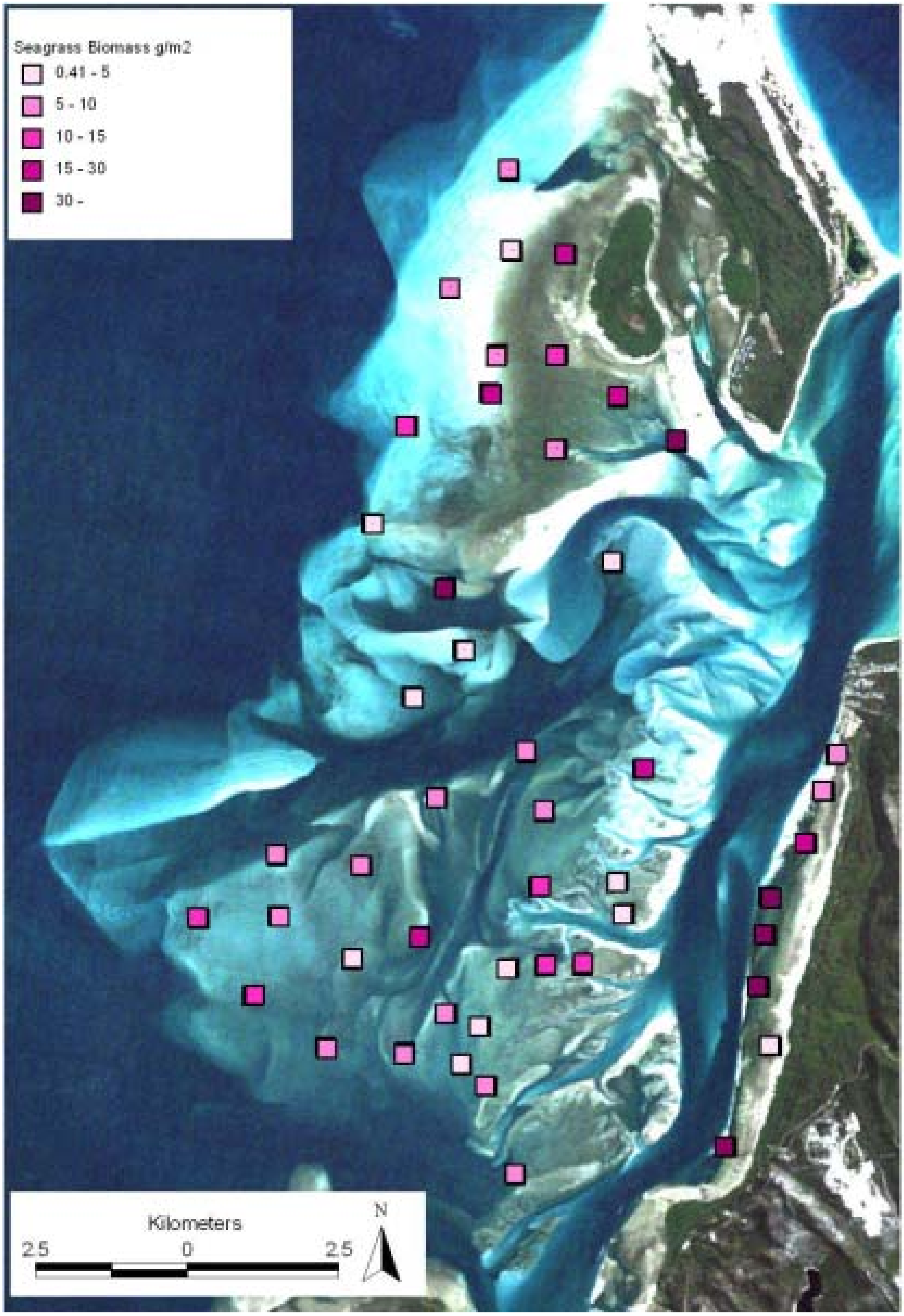
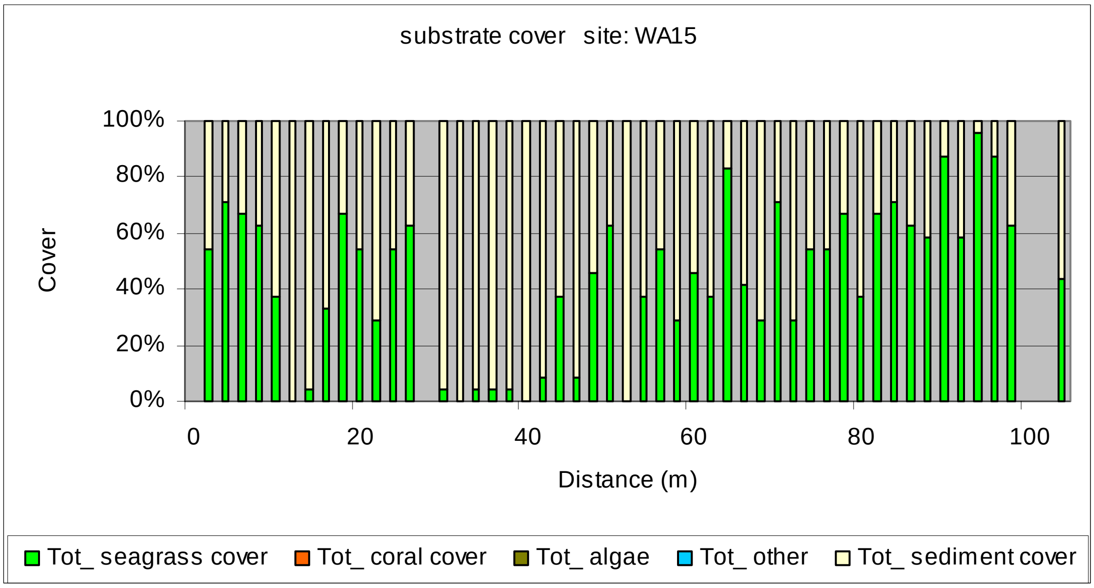


Figure 17. Transect-level summaries for field survey of seagrass above-ground biomass, collected from Eastern Banks in July 2004



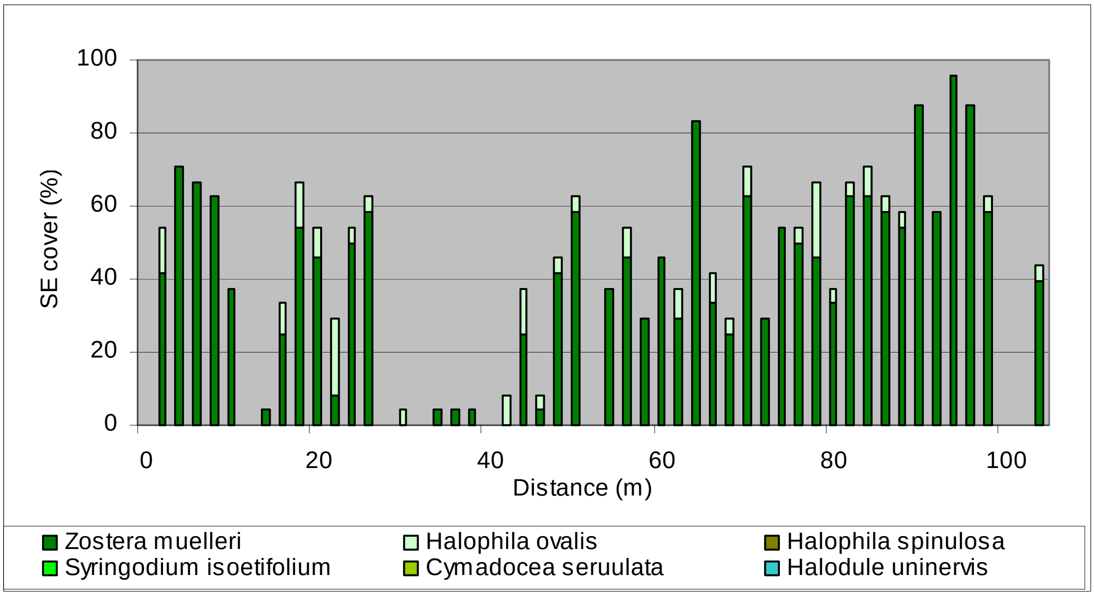


Figure 18. Example output for photo-level analysis at 2.0 m interval along 100 m: (a) substrate cover composition; and (b) species composition. These data were collected from 84 transects covering Eastern Banks in July 2004.

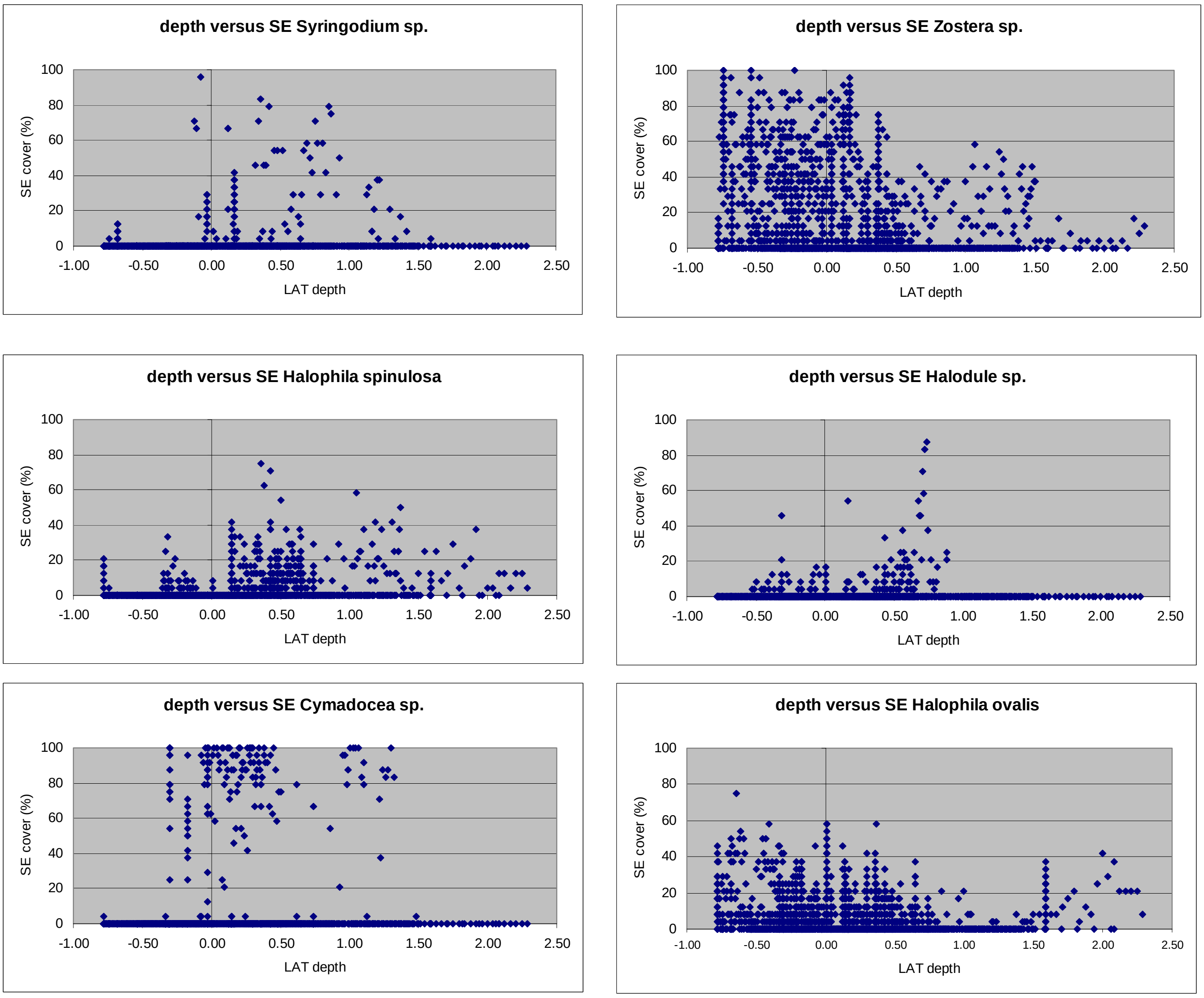
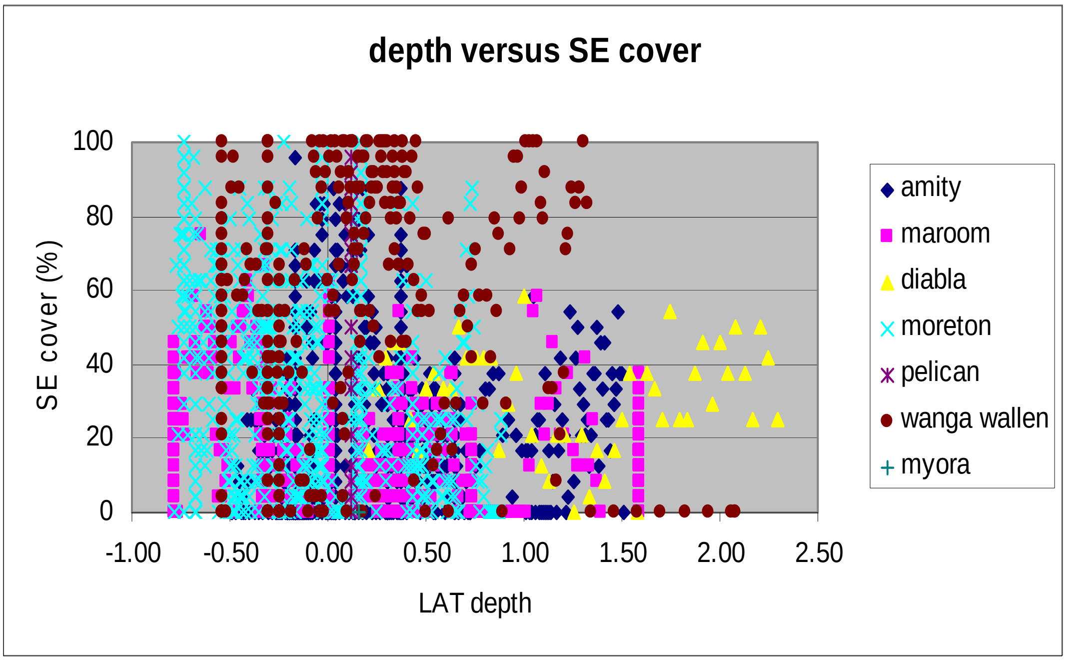


Figure 19. Example output for analysis of seagrass species–depth associations for the species sampled on the Eastern Banks in July 2004



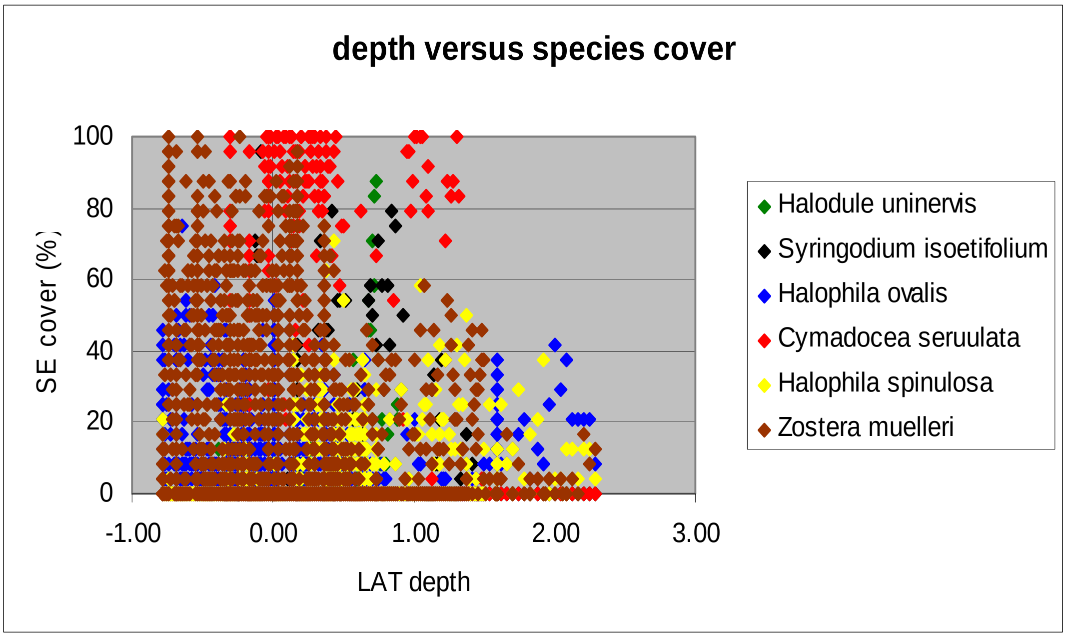


Figure 20. Seagrass species density (cover)–depth associations for all field sample points, where LAT depth = depth below lowest astronomic tide

5.2 Seagrass density maps—Eastern Banks and Moreton Bay

Similar trends in spatial variations in seagrass density were observed across the density maps produced from each of the three sensors (Figures 21a to 21c). The differences in the extent of mapped areas from each sensor was due to the area covered by each, with Quickbird-2 and CASI-2 images only covering a section of the Eastern Banks. Tidal stage also affected the areas mapped, with the Quickbird-2 and CASI-2 images being acquired at a lower tide, resulting in more exposed and unmapped areas. The mapped patterns match up with the transect-level summaries of seagrass density shown in Figure 15. Consistent spatial patterns matching the field survey are evident in the maps, and are shown in more detail across each image data set. Lower-density areas (< 40%) dominated the shallow western section of all of the banks. The highest cover areas were found in shore-parallel bands in the more sheltered areas of Wanga Wallen Banks and the bank immediately west of Crab Island at the southern tip of Moreton Island. The higher spatial resolution images also revealed very high-density circular patches of *Cymodocea serrulata* throughout the eastern sections of Amity Banks. These circular patches were very distinct and ranged in diameter from 2 m to 15 m and appeared to merge together to form larger mono-specific patches.

Figure 22 shows the Bay-wide map of seagrass density produced by a combination of field survey from EHMP spot-checks and data from the Landsat 5 TM image of the clear waters on the Eastern Banks and south-western shore of Moreton Island and exposed inter-tidal areas in the western Bay (Godwin Beach–Deception Bay, Waterloo Bay, Rose Bay, Raby Bay and the southern section of Moreton Bay). Low to moderate density levels of seagrass were dominant in most of the western inter-tidal areas.

Figure 21a. Seagrass density maps to 3.0 m depth for the Eastern Banks, derived from Landsat 5 TM image

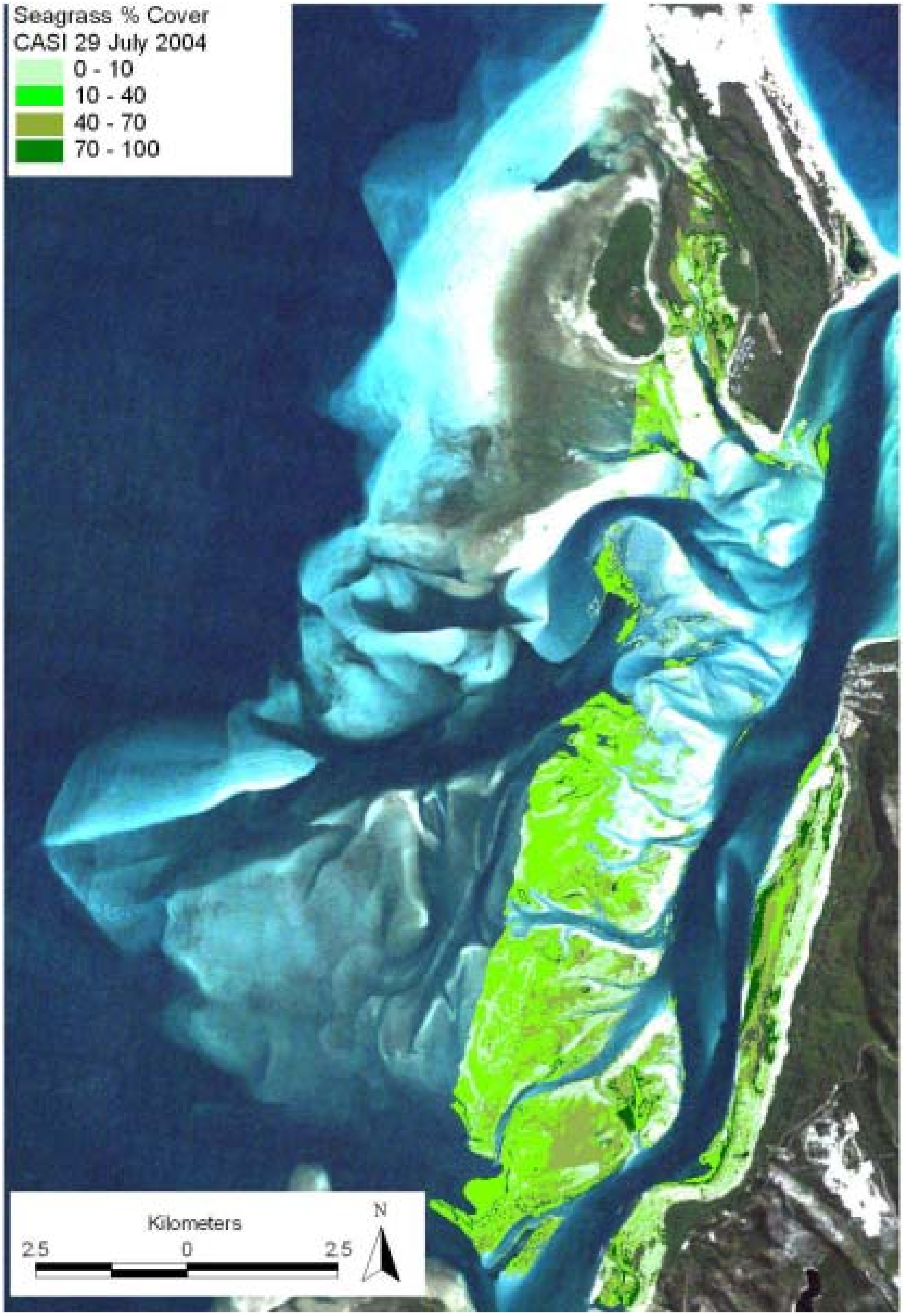


Figure 21b. Seagrass density maps to 3.0 m depth for the Eastern Banks, derived from CASI-2 image

Figure 21c. Seagrass density maps to 3.0 m depth for the Eastern Banks, derived from Quickbird-2 image

Figure 22. Seagrass density map for Moreton Bay derived from the integration of Landsat 5 TM image classes (Eastern Banks and inter-tidal western bay) and field survey from QPWS Marine Parks and EHMP (remainder of Bay). The areas not coloured in the Bay were either too deep or turbid to be mapped with the techniques we used.

5.3 Seagrass species composition maps—Eastern Banks

Seagrass species maps were only able to be derived from the higher spatial resolution CASI-2 and Quickbird-2 images due to the small width and heterogeneous nature of seagrass patches in the Eastern Banks, which would not be detected in a 30 m x 30 m Landsat 5 TM pixel. Overall patterns in species composition mapped were similar between the CASI-2 and Quickbird-2 images (Figure 23), and both maps provided similar but more detailed versions of the species composition trends identified from the field survey transects (Figure 16). The main differences between the two image maps shown in Figure 23 are due to tidal stages. The CASI-2 image was captured at a significantly lower tidal stage than the Quickbird-2 image, which resulted in large areas of *Halophila ovalis* not being mapped in the CASI-2 image as they were exposed. The depth–species plot (Figure 20) derived from the field data survey data shows that *Halophila ovalis* was observed at depths from 1.0 m above to 0.5 m below the mean sea level, supporting the loss of this species from the low-tide image.

The main zones observed in the seagrass maps coincided with those identified from the visual assessment of the transect-level seagrass species composition data shown in Figure 16, which were:

(1) high to moderate density levels on the Wanga Wallen Banks, with mono-specific zones of *Zostera* sp., *Cymodocea* sp. and *Halophila syringodium*

(2) low to medium density on the eastern sections of Eastern Banks with a mix of *Zostera sp*. and *Halophila ovalis*

(3) the western section of the Eastern Banks and Maroon Banks dominated by low to moderate densities of mixed species assemblage of *Halophila spinulosa* and *Halophila ovalis*

(4) the bank immediately south-west of Crab Island, dominated by high densities of *Zostera* sp.

(5) the western section of the previous zone, consisting of low to medium density levels with mixtures of *Halodule* sp., *Halophila ovalis* and *Halophila syringodium.*

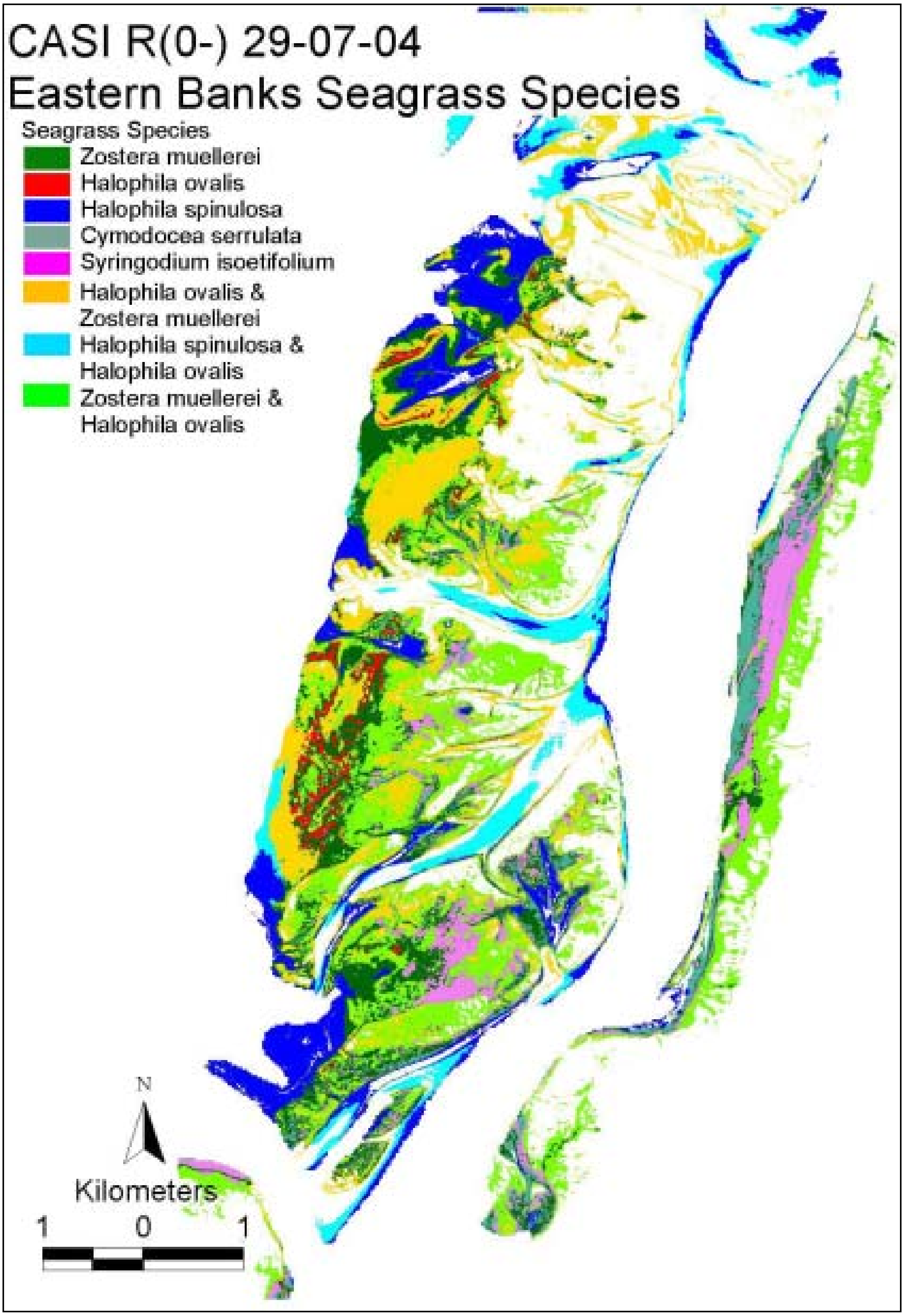


Figure 23a. Seagrass species composition maps to 3.0 m depth for the Eastern Banks, derived from Quickbird-2 image

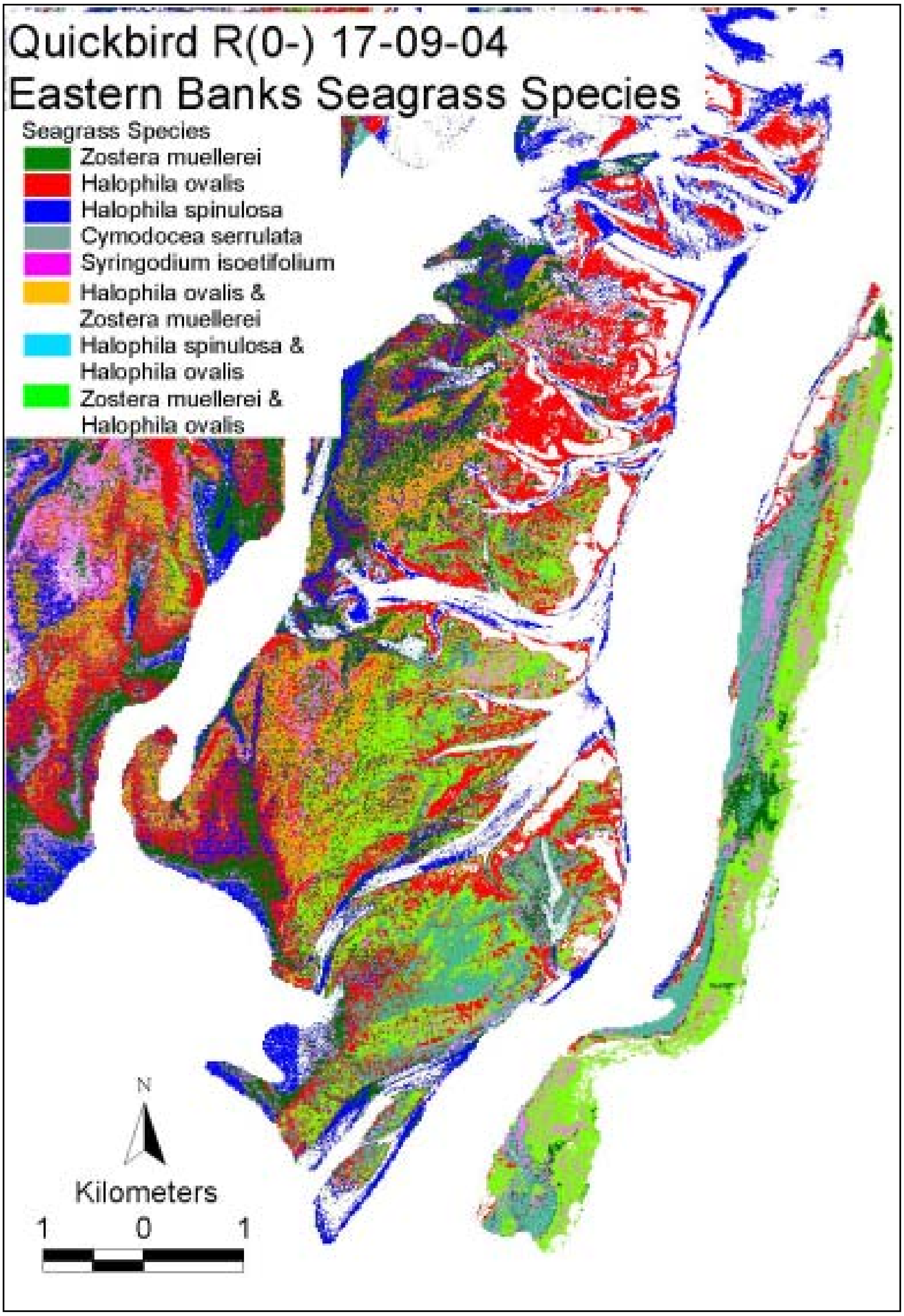


Figure 23b. Seagrass species composition maps to 3.0 m depth for the Eastern Banks, derived from CASI-2 image

5.4 Seagrass biomass maps—Eastern Banks

Due to more limited sampling of biomass (two sites per transect), the field samples only provided a partial, point-based assessment of the above-ground biomass distribution (Figure 17) in contrast to the image-based estimates (Figure 24). The overall patterns in biomass were similar to those mapped for seagrass density (Figure 22), but had variations due to the species specific variations in seagrass structure, which resulted in spatial variations in biomass. This was apparent in both the Quickbird-2 and CASI-2 biomass maps, with areas of high density of *Halophila spinulosa* and *Cymodocea serrulata* exhibiting distinctly higher biomass values than surrounding seagrass with high biomass levels. Similar overall trends in biomass between mapped and field sampled data showed that mono-specific areas in sheltered locations exhibited the highest biomass, with the areas of high biomass being the Wanga Wallen Banks and area immediately to the south-west of Crab Island. Both the CASI-2 and Quickbird-2 images are showing the same relative spatial patterns in biomass, but with slightly different actual numbers. This may be due to the more suitable bands and higher radiometric resolution of the CASI-2, being able to map greater detail in the density of seagrass and relate it to field data.

Figure 24a. Seagrass above-ground biomass maps to 3.0 m depth for the Eastern Banks, derived from Quickbird-2 image

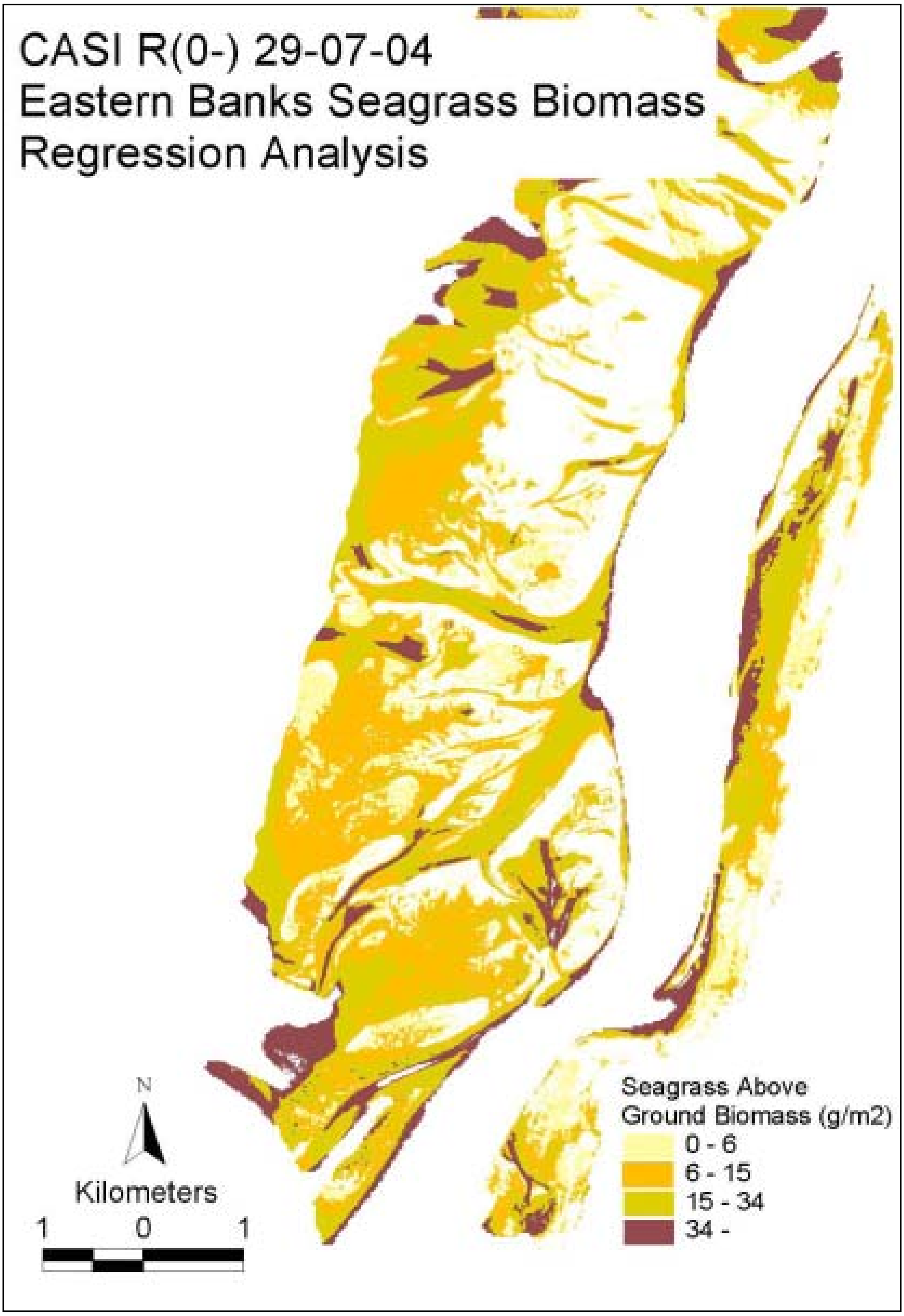


Figure 24b. Seagrass above-ground biomass maps to 3.0 m depth for the Eastern Banks, derived from CASI-2 image

5.5 Integrated depth, water quality and benthic cover mapping

Figures 25 and 26 show the bathymetry map for the eastern portion of Eastern Banks derived from CASI-2 image using a two-substrate library. The bathymetry map is overlaid with the bathymetry vectors supplied by Queensland Department of Transport. Figure 27 depicts the error image associated estimate of percentage brown mud, based on the difference between modelled and actual image values.

Results for the inversion of the CASI-2 imagery of the north-eastern portion of Eastern Banks using the full spectral library (Figure 12), in Table 6 are reported in Figures 28 to 30. Figure 28 presents an example benthic cover map for the north-eastern portion of Eastern Banks as the percentage of the cover of one of the twelve substrates. Figure 29 presents the concentration maps of the water column constituents (chlorophyll-Ŭ, CDOM and tripton). Figure 30 presents the difference image between bathymetric surfaces for the western part of Eastern Banks calculated from the CASI-2 image using a two- and a twelve-substrate library. Figure 31 presents the bathymetric map for the western portion of Eastern Banks derived from CASI-2 image using a two-substrate library. The bathymetry map is presented with the bathymetry vectors supplied by Queensland Department of Transport. Figure 33 presents the benthic cover type map for the western portion of Eastern Banks derived from CASI-2 image using a two-substrate library. Figure 34 presents the bathymetric map for the Brisbane River derived from CASI-2 image using a two-substrate library. The bathymetry map is presented with the bathymetry vectors supplied by Queensland Department of Transport. Figure 35 depicts the error image associated estimate of percentage brown mud, based on the difference between modelled and actual image values. Figure 36 depicts the benthic cover map for the western portion of Eastern Banks as the percentage of the darkest substrate (brown mud).

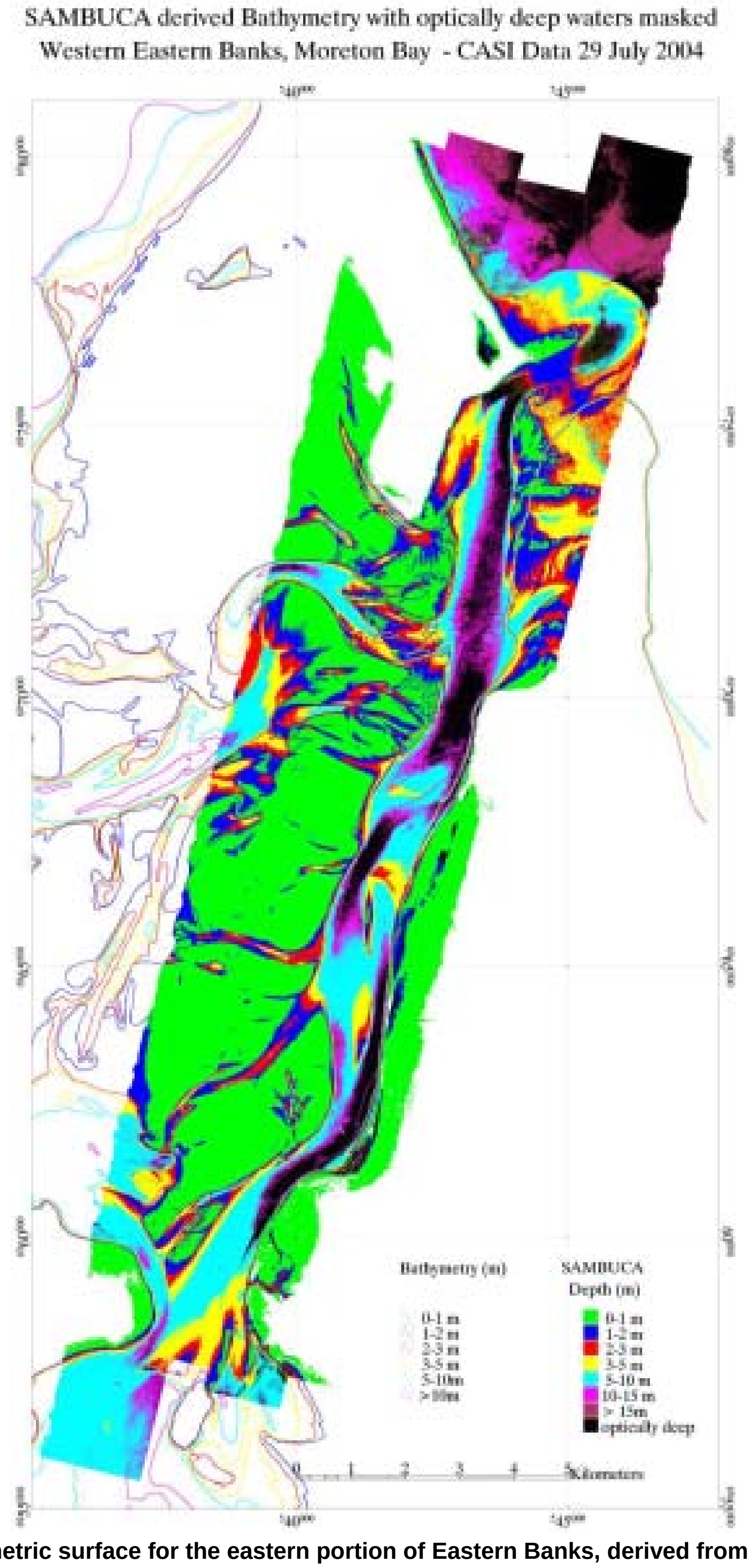


Figure 25. Bathymetric surface for the eastern portion of Eastern Banks, derived from CASI-2 image using a two-substrate library (brown mud and white sand). The bathymetry map is presented with the bathymetry vectors supplied by Queensland Department of Transport.

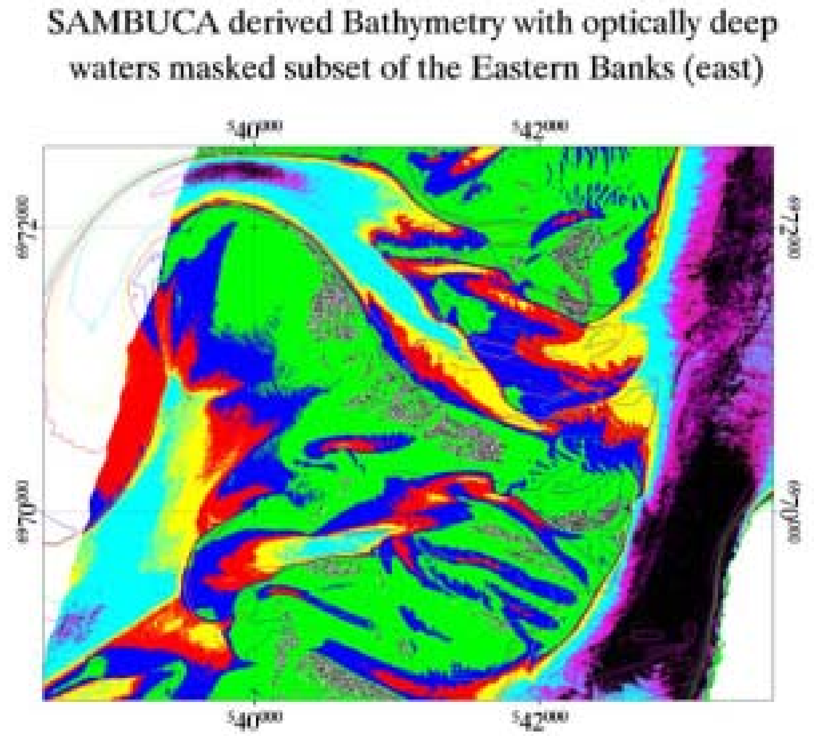


Figure 26. A subset showing the detail of the bathymetric surface for the eastern portion of Eastern Banks, derived from CASI-2 image using a twelve-substrate library. The bathymetry map has the same key as presented in Figure 25.

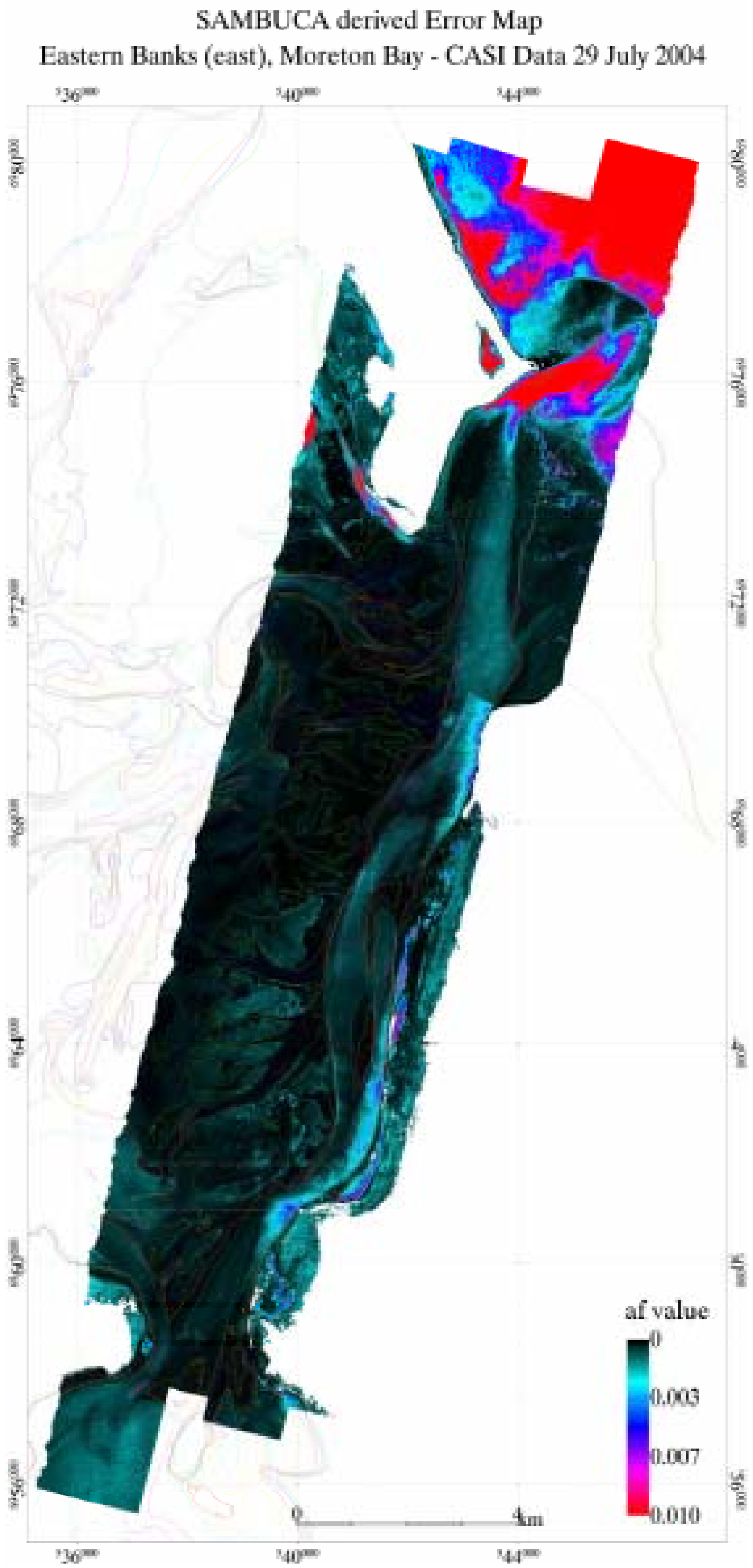


Figure 27. Example error image for the eastern portion of Eastern Banks CASI-2 image using a twelve-substrate library.

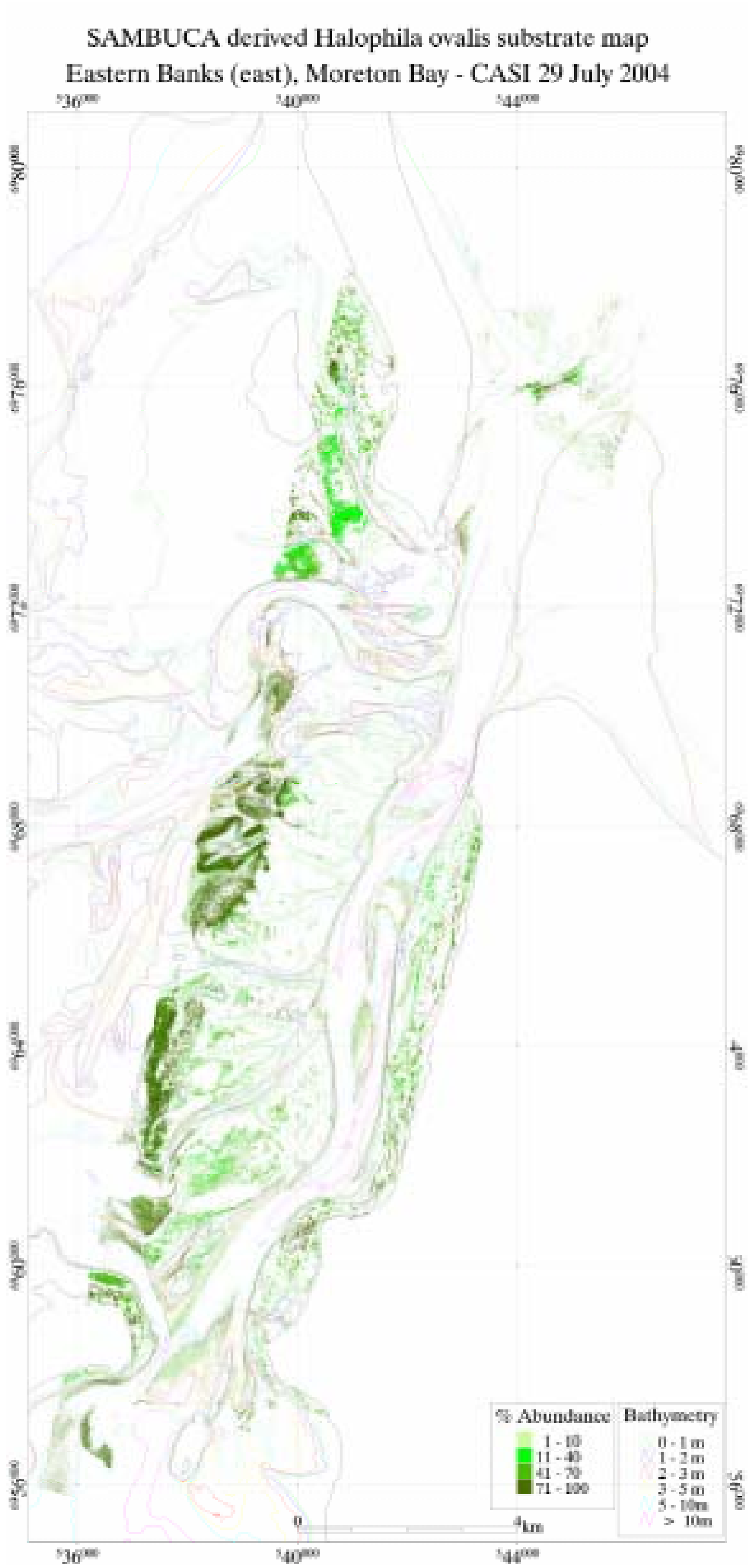


Figure 28. Example output fraction maps showing the area of each pixel covered by a specific benthic cover type for the eastern portion of the Eastern Banks, derived from CASI-2 image using a twelve-substrate library (full list in Table 6)

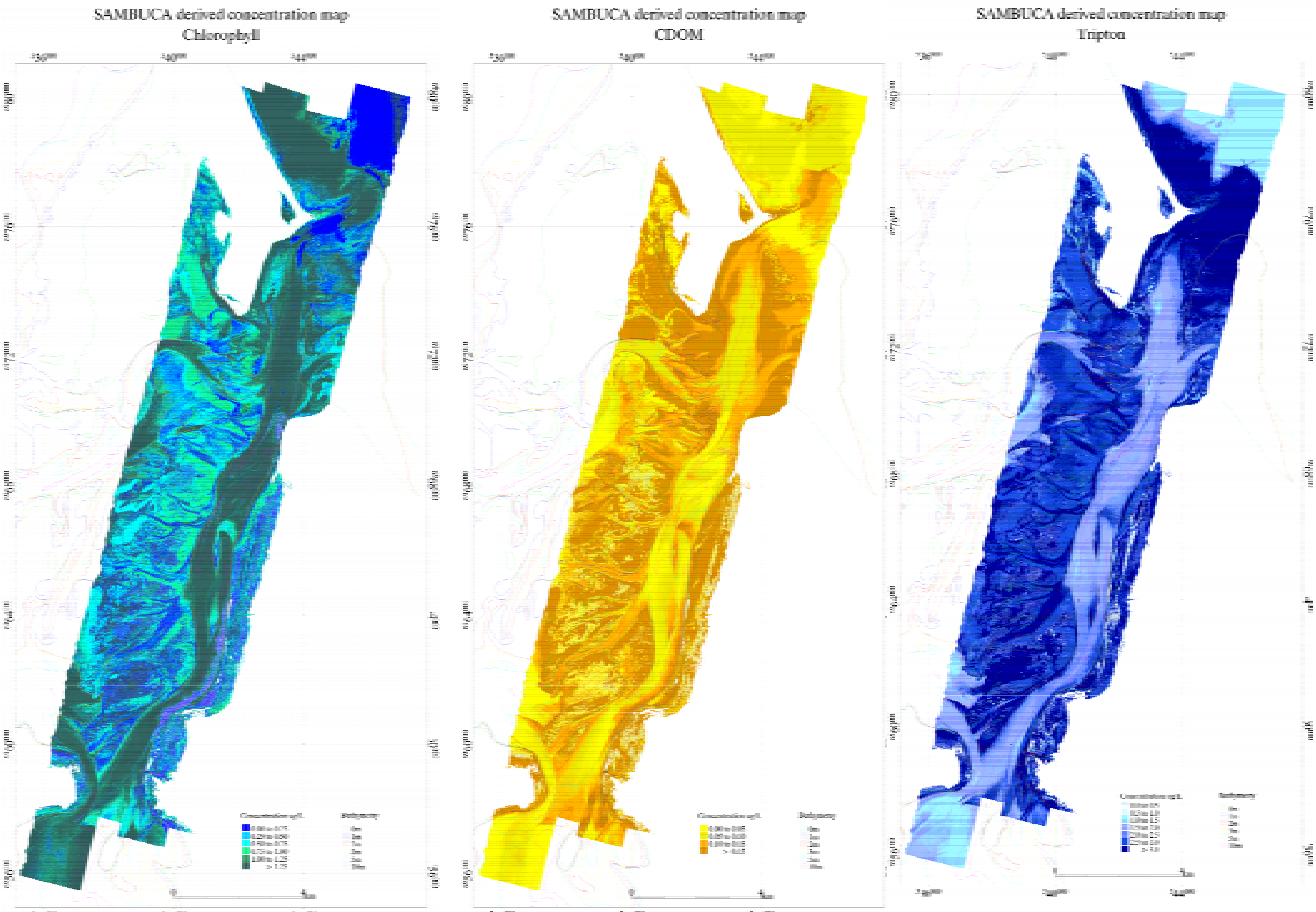


Figure 29. Water column constituents (chlorophyll-Ŭ, CDOM and tripton) concentration maps for the eastern portion of Eastern Banks, derived from CASI-2 image using a twelve-substrate library

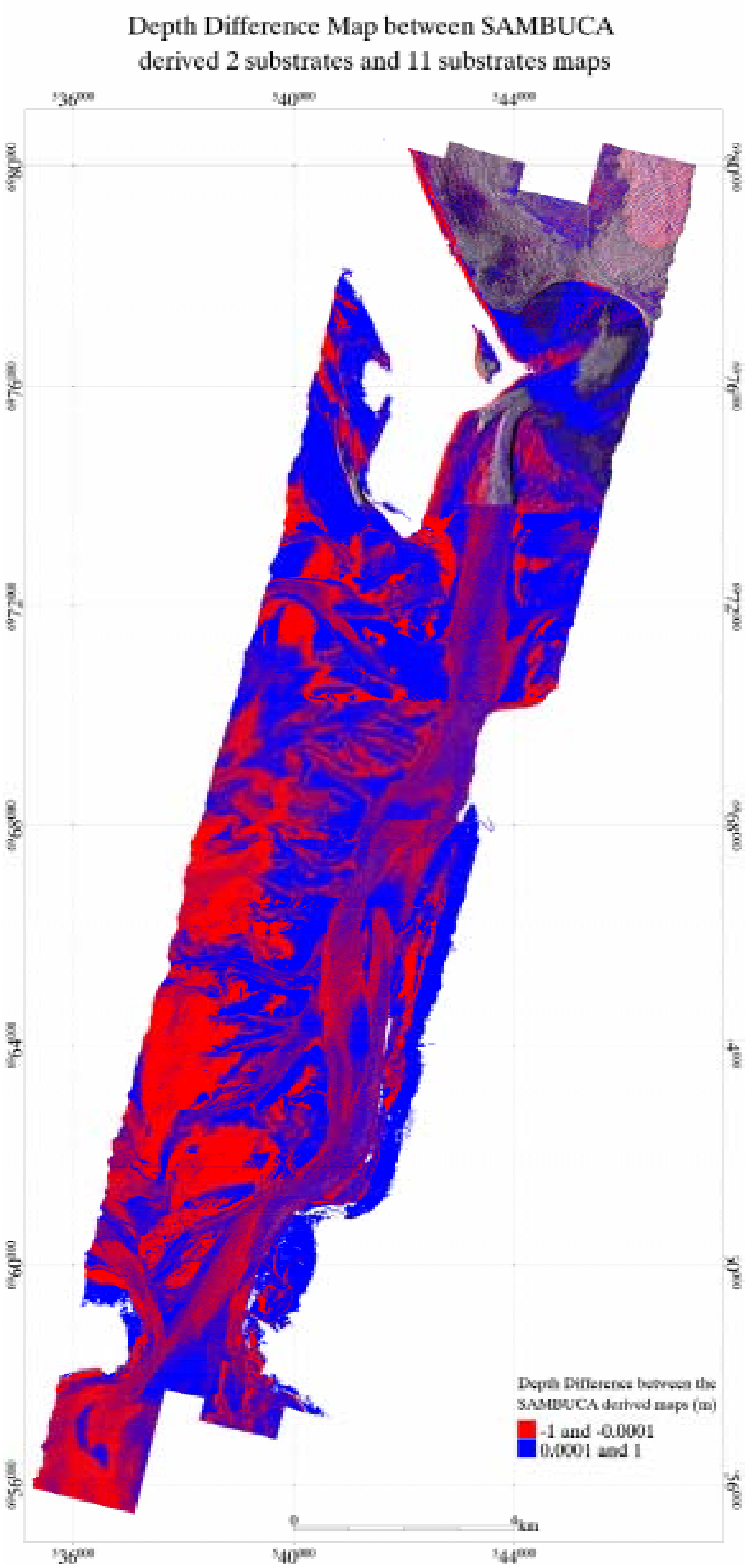


Figure 30. Depth difference image (predicted – actual) for the eastern portion of Eastern Banks CASI-2 image using a two- and a twelve-substrate library

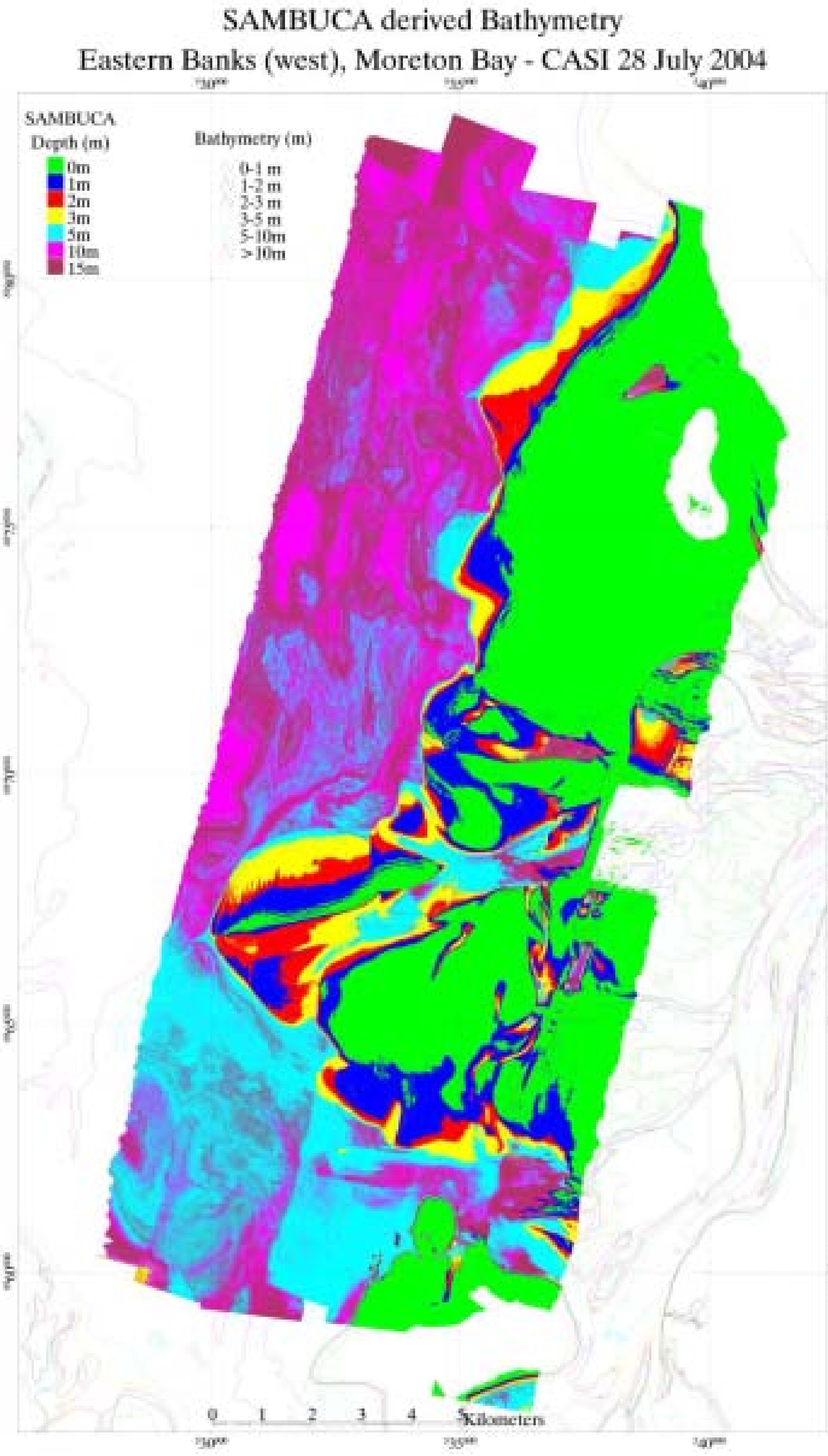


Figure 31. Western portion of Eastern Banks bathymetric surface, derived from CASI-2 image. The bathymetry map is presented with the bathymetry vectors supplied by Queensland Department of Transport.

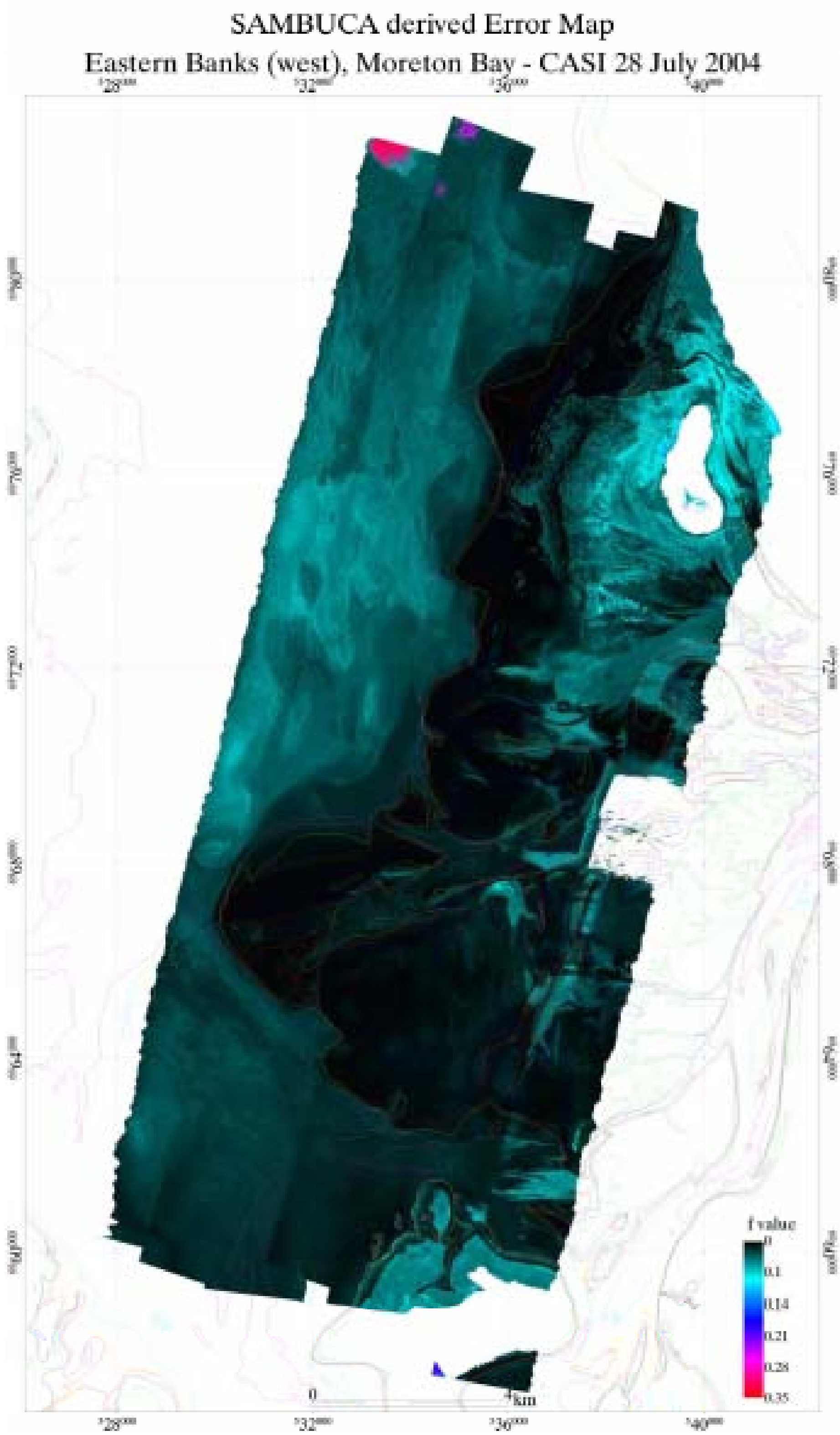


Figure 32. Example error image for the western portion of Eastern Banks CASI-2 image using a two-substrate library

Figure 33. Benthic cover fractions and benthic cover maps for the western portion of Eastern Banks, derived from CASI-2 image using a two-substrate library (brown mud and white sand)

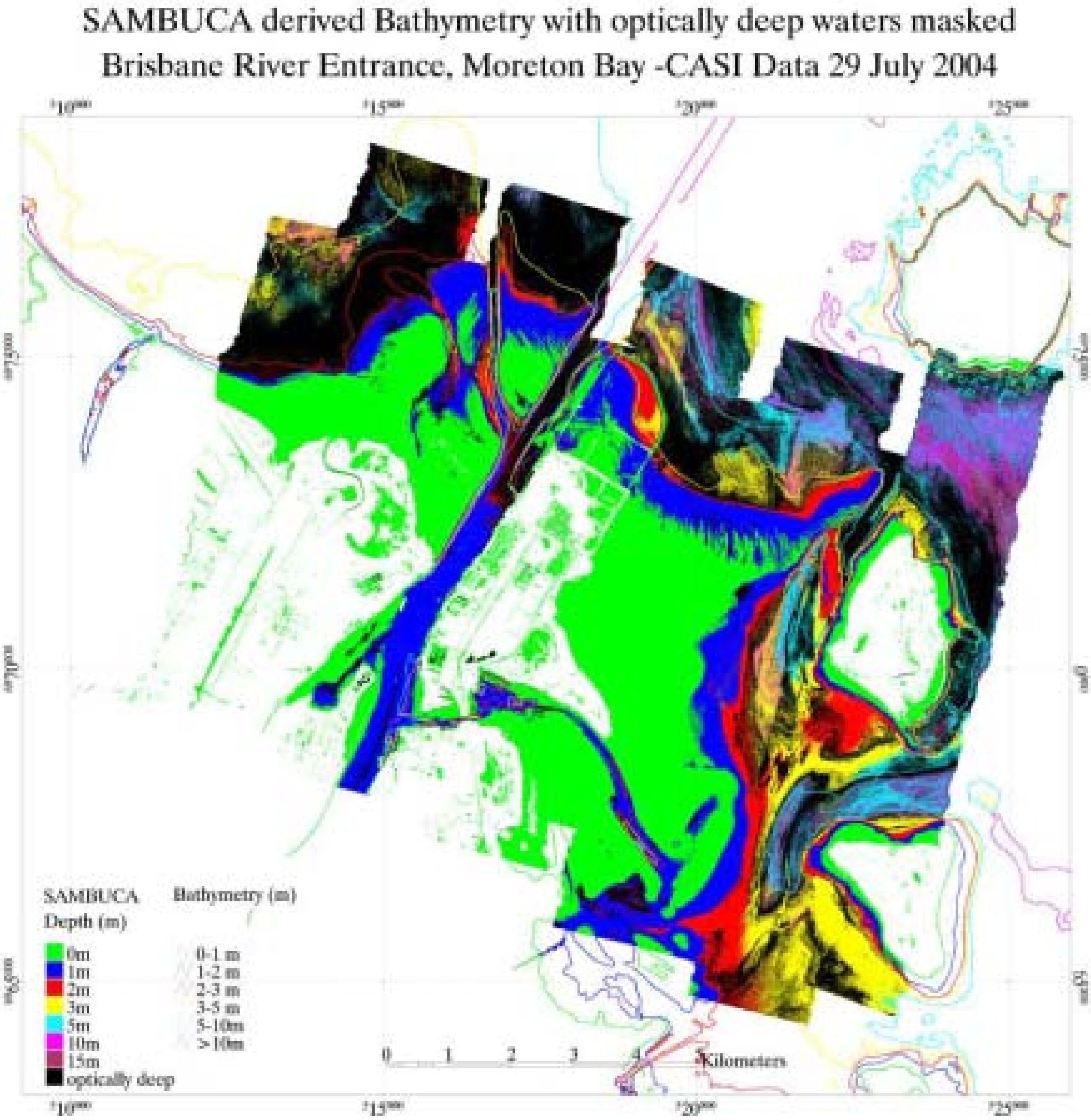


Figure 34. Brisbane River bathymetric surface derived from CASI-2 image. The bathymetry map is presented with the bathymetry vectors supplied by Queensland Department of Transport.

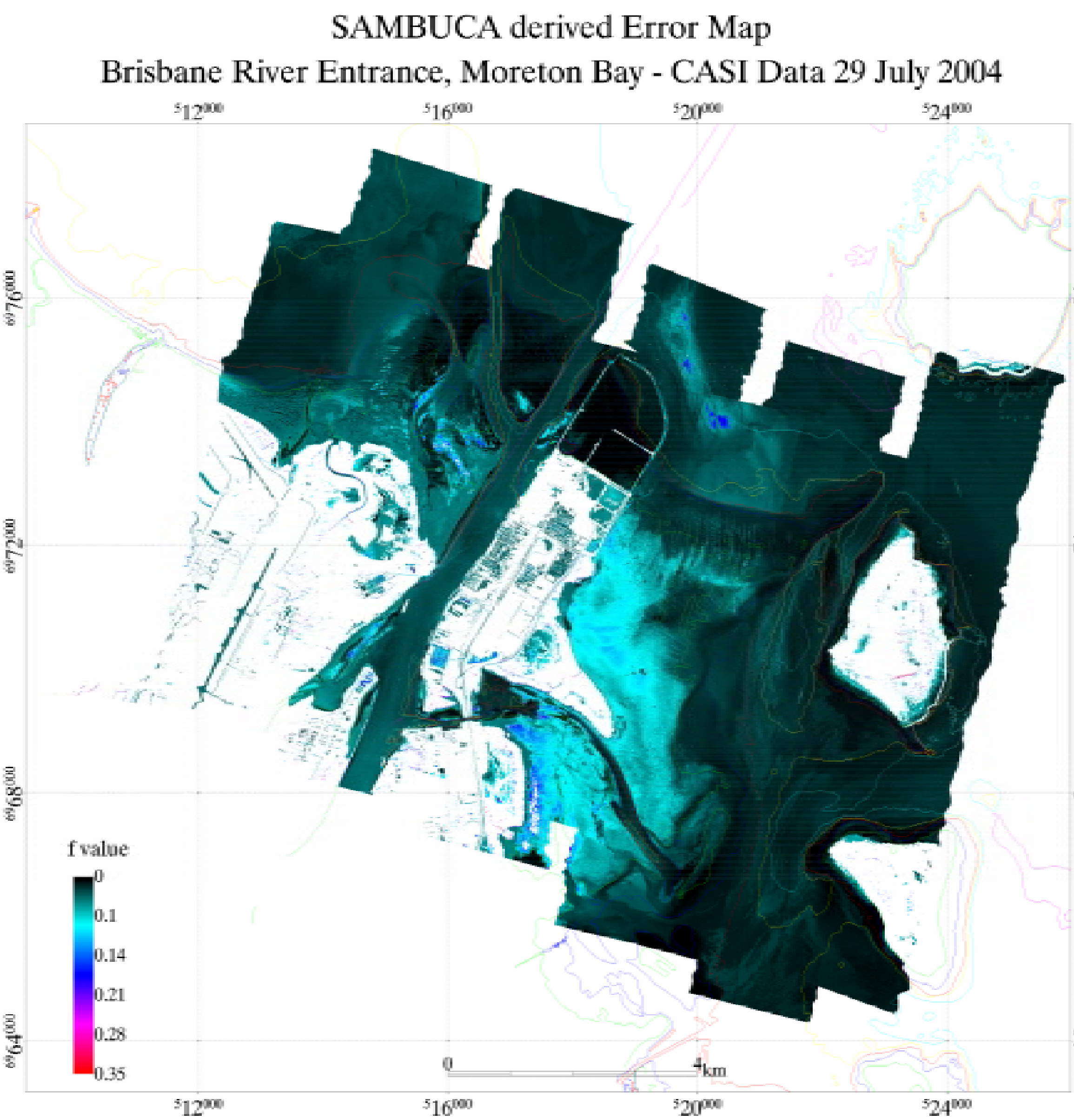


Figure 35. Example error image for the Brisbane River CASI-2 image using a two-substrate library

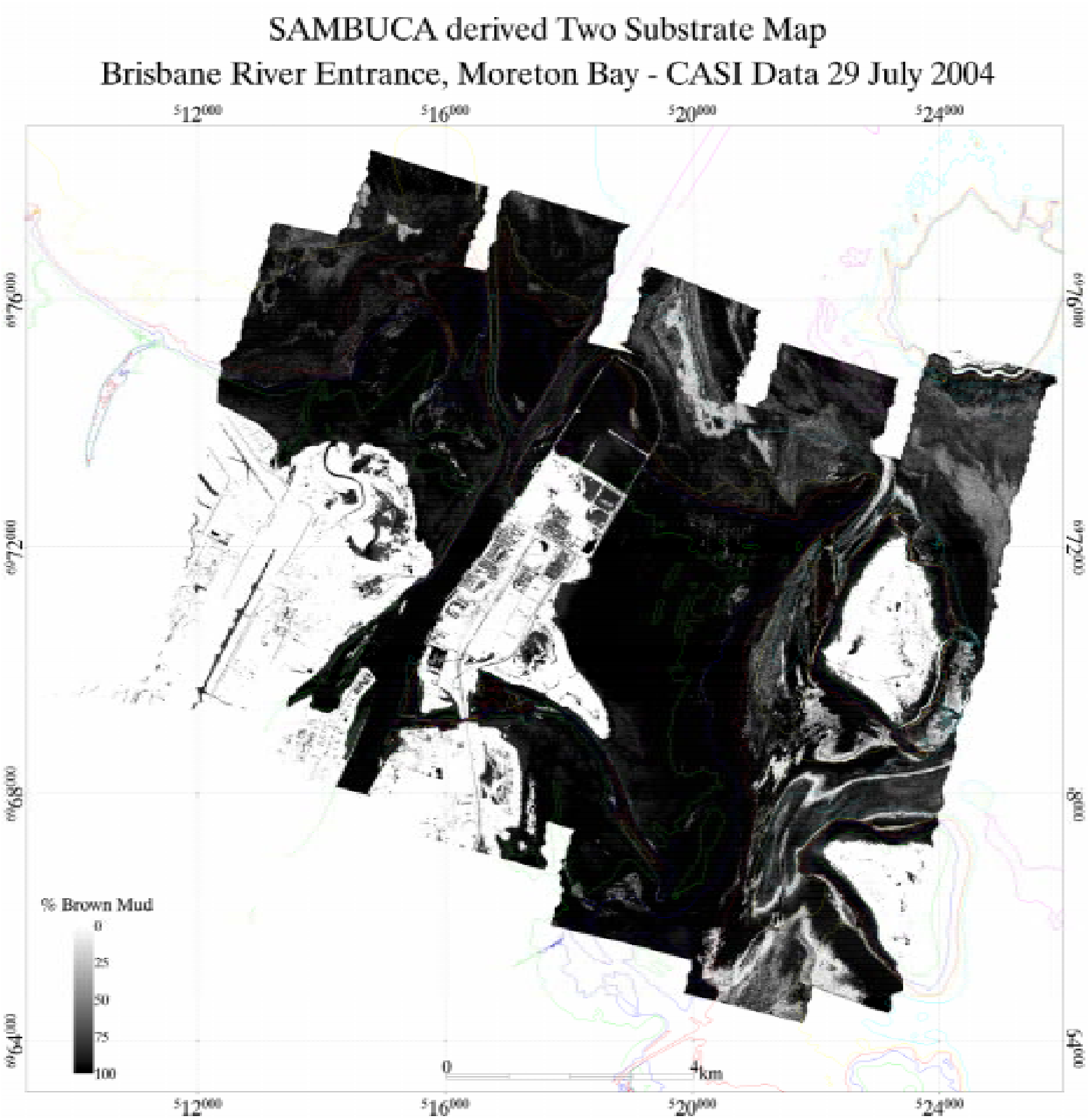


Figure 36. Benthic cover fractions and benthic cover maps for the Brisbane River, derived from CASI-2 image using a two-substrate library (brown mud and white sand)

5.6 Error and accuracy assessment—a comparison of mapping results from commercially available image data sets

Our approach to error assessment for seagrass density, species and biomass maps was based on the field data sets (Figure 14), which allowed us to train (calibrate) and validate our maps from each sensor (Landsat 5 TM, Quickbird-2 and CASI-2). For the seagrass density and species maps, error assessment was carried out by checking output maps against both the data used for calibration and validation purposes. With the exception of the biomass maps, the reported accuracy levels should be interpreted at an individual pixel level, as the probability that the pixel is correctly labelled. For example, an overall accuracy of 75% means that for each pixel the probability it is correctly labelled is 75%, with a 25% probability that it was mislabelled. The individual class accuracy levels are interpreted in a similar manner, i.e. an individual class accuracy of 85% means that for each pixel in that class the probability it is correctly labelled is 85%, with a 15% probability that it was mislabelled. The calibration data comparison should have accuracy levels > 90% in all classes if the algorithms were trained appropriately. In each case, standard error assessment techniques from image processing were used (Congalton 1991) and 'producer accuracy' levels, i.e. probability that a pixel is correctly classified, were reported. As regression models were used to derive the above-ground biomass maps, the R^2 values and scatterplots used to define these models were analysed.

For all types of seagrass map products, in a shallow clear environments such as those covered in this work, airborne hyperspectral data consistently produced maps with the highest accuracy from both calibration and validation data sets, closely followed by the high spatial resolution satellite multispectral sensor data (Figures 37 to 39). Consistently low accuracy levels were recorded by the multispectral Landsat 5 TM sensor. The reason for the high levels of accuracy from the airborne image data were: high spatial resolution (i.e. pixel size < 5 m x 5 m), very high radiometric resolution (ability to detect small changes in brightness) and use of spectral bands in regions most suited to mapping submerged aquatic vegetation. The satellite multispectral image data were also highly accurate due to its small pixel size and high radiometric resolution. However, the Landsat 5 TM data lacked suitable spatial resolution, spectral and radiometric resolution for mapping seagrass properties.

In terms of mapping seagrass density in waters < 3 m deep in Moreton Bay, the airborne hyperspectral image data returned high accuracies across all density levels from very high to very sparse (Figures 37b and 37c). In contrast, both Quickbird-2 and Landsat 5 TM were unable to differentiate moderate to low and sparse levels of seagrass density. In Landsat 5 TM image data this is expected to be a function of pixel size. However in the Quickbird-2 image, its limited number of broad spectral bands do not allow for the same amount of discrimination as the CASI-2, even though it has similar radiometric resolution. The reason for this can be seen in the plot of reflectance against biomass for the Quickbird-2 and CASI-2 data sets in Figures 39a and 39b, with the Quickbird-2 image data saturating at high biomass levels.

The airborne hyperspectral data also produced the highest mapping accuracies for seagrass species maps, due to high levels of accuracy across all of the classes mapped on the Eastern Banks (Figure 38). Discrimination of both mono-specific and the most commonly occurring mixtures of seagrass species was possible with the CASI-2 data, mainly due to the specific set of spectral bandwidths and radiometric resolution of the sensor. The general-purpose, wide spectral bands of the Quickbird-2image did not able discrimination of the mixed seagrass classes and the very sparse growth form of *Syringodium isoetifolium*. Species mapping was not attempted with Landsat 5 TM data as exploratory analysis indicated this was not possible, primarily due to the size of its pixels and the size of the areas to be mapped.

The greater dynamic range and selection of spectral band placement and width to minimise water column attenuation in the CASI-2 data set was responsible for its high level of sensitivity to seagrass biomass, up to high biomass levels. Figure 36 shows the effects of increasing biomass and reduced reflectance in both the Quickbird-2 and CASI-2 images, with the latter image retaining a greater sensitivity to higher biomass levels.

Interpretations of the accuracy assessment results for each seagrass property and for the three forms of commercially available image data can also be used to identify factors reducing the accuracy of these data sets, and areas in which further work is needed. These areas now include:

- depth limitations, i.e. how far beyond 3 m can we map properties in clear water with airborne hyperspectral and satellite high-resolution multispectral?
- water clarity, i.e. to what level of clarity (Secchi depth?) can we conduct this type of mapping

- seagrass type and density, i.e. more work is needed to improve mapping approaches for sparsely occurring and mixed species assemblages.

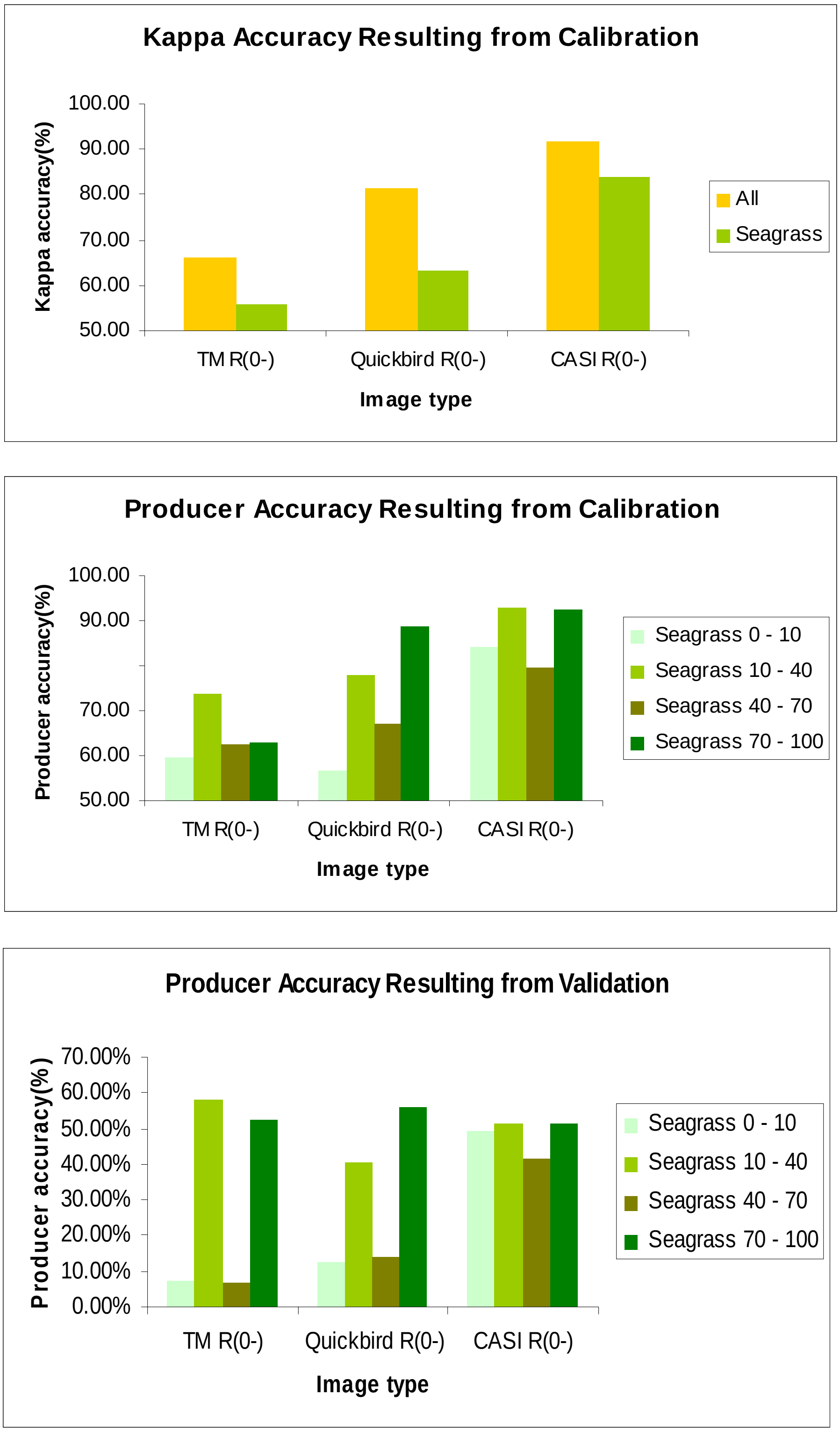
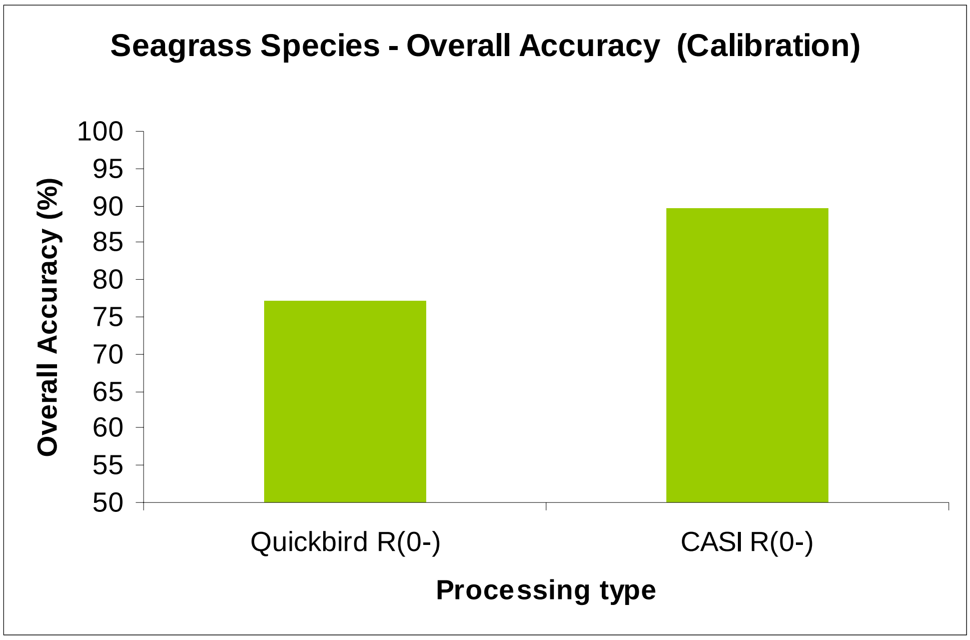


Figure 37. Overall accuracy of seagrass density maps for Landsat 5 TM image, CASI-2 image and Quickbird-2 image: (a) adjusted overall accuracy (kappa) from calibration sites; (b) overall accuracy from calibration sites; and (3) overall accuracy from validation sites.



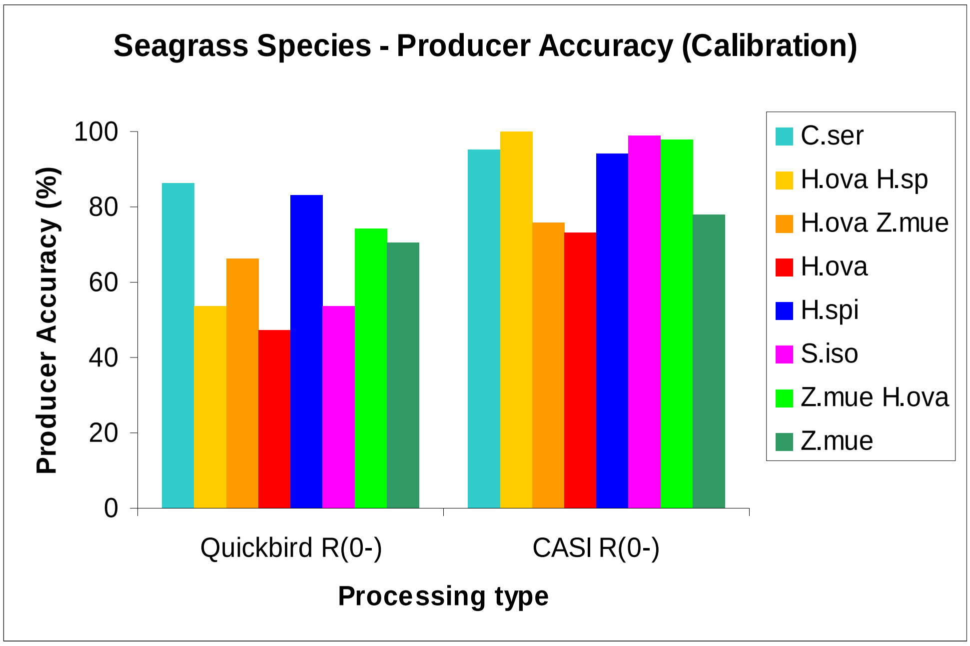


Figure 38. (a) Overall accuracy of seagrass species maps for CASI-2 image and Quickbird-2 image from calibration data; and (b) Individual class overall accuracy of seagrass species maps for CASI-2 image and Quickbird-2 image from calibration data

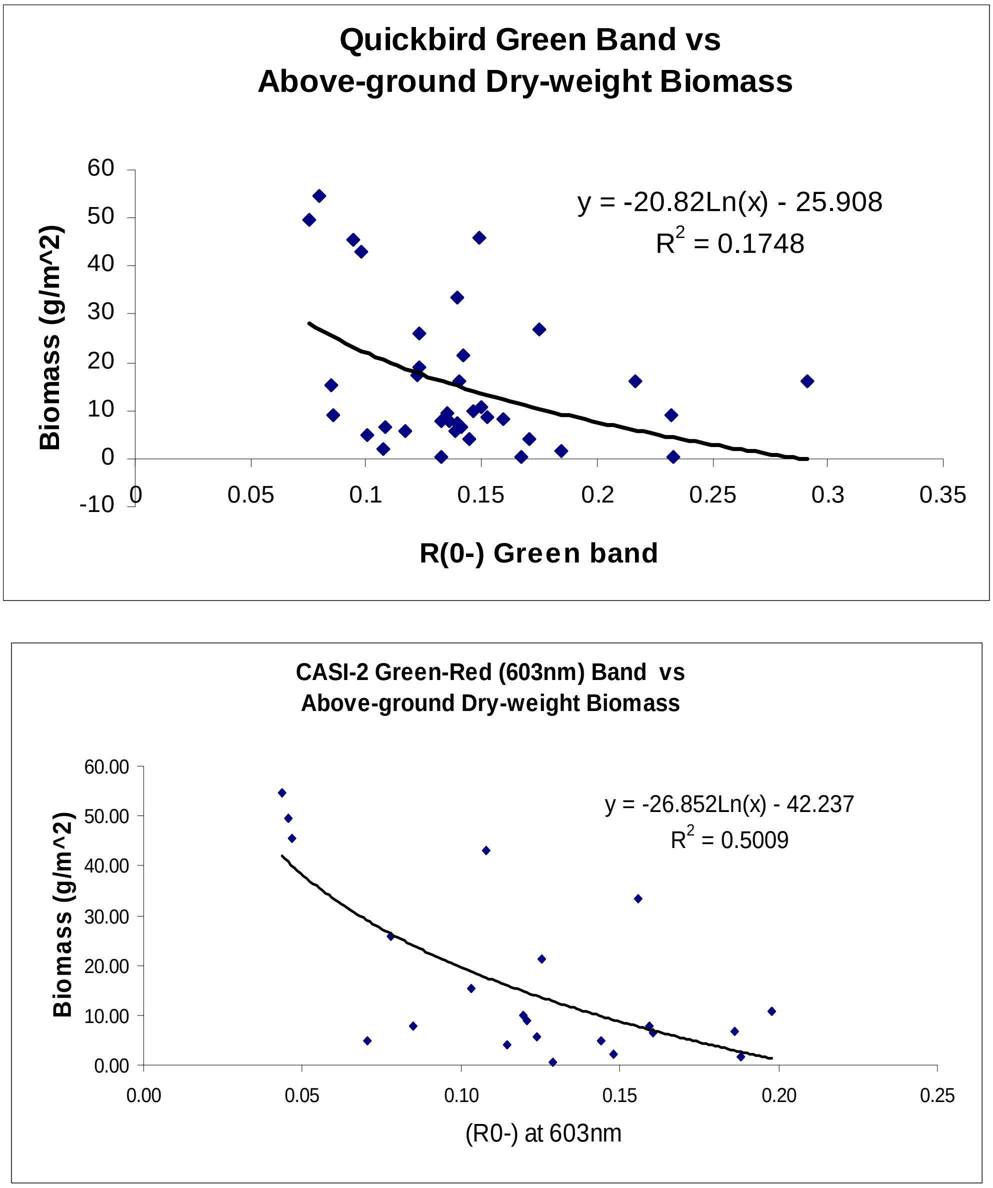


Figure 39. Scatterplots and regression models used for estimating seagrass above-ground dry-weight biomass maps for (a) Quickbird-2 image; and (b) CASI-2 image

6 Benefits and outcomes

The main beneficiaries of this work will be technicians, scientists and managers who require information on seagrass distribution and its properties in Moreton Bay. More generically, our findings will be of benefit to those who need to know which type of image data set and processing approach are required for mapping seagrass across a range of water clarity levels in sub-tropical coastal environments. In a local context, the maps produced will be used by the Ecosystem Health Monitoring Program (EHMP—Moreton Bay Waterways and Catchments Partnership) and Queensland EPA's Marine Parks divisions for monitoring and management. The approaches developed have been presented at the premier international conference on shallow water mapping (AGU/ASLO Ocean Sciences 2006) and submitted for publication in internationally peer reviewed journals which focus on mapping techniques which are used by scientists and managers working in this area.

The specific outputs and outcomes with direct relevance to the Australian and International seagrass mapping communities are:

- This project demonstrated the benefit of inter-agency collaboration for collecting, processing, mapping and disseminating spatial information for natural resource science, monitoring and management.
- An urgently needed baseline data set for seagrass density across Moreton Bay, and species composition and biomass across the Eastern Banks was developed and validated, and placed in a commonly accessible format for or science, monitoring and management.
- At the time of writing this report the authors are discussing how to continue this approach with the agency responsible for seagrass monitoring and management in Moreton Bay, to reduce the amount of field survey they undertake and to provide a spatially complete coverage of Moreton Bay.
- The study provides the first international, fully objective evaluation of the accuracy of a range of commercial image data sets and the full range of processing techniques from simple to complex, to produce maps on benthic cover attributes. The results from this comparison will enable mapping technicians, scientists and manners to select objectively from the data and processing technique most suited to a specific application area and problem.

- Following on from the last point, the results of this work also make a significant contribution to seagrass ecology and remote sensing science. Our findings demonstrate which image data/processing technique combination is most suitable.

Outcomes in comparison to original aims

The main objective of this work "was to produce and verify maps of benthic substrate types (e.g., seagrass, algae, coral, sand or mud) and their biophysical properties for sections of Moreton Bay using airborne and satellite image data sets." This task has been completed fully with respect to seagrass mapping, which was considered to be the benthic habitat type of most interest to monitoring and management agencies in Moreton Bay. In relation to secondary objectives:

(1) we collected, and delivered in a georeferenced GIS, set of field survey data on seagrass species, density and above-ground biomass for as many sites in Moreton Bay as possible

(2) we collected and delivered georeferenced, atmospherically and air–water interface corrected airborne hyperspectral (CASI-2) and satellite multispectral (Quickbird-2, Landsat 5 TM) images for Moreton Bay during the same period that field survey data were collected

(3) all image data were processed to produce maps of seagrass density, seagrass species composition and above-ground seagrass biomass for specific sections and all of Moreton Bay

(4) the airborne hyperspectral data was used to map water depth, water quality and substrate cover types

(5) the accuracy level of each image–seagrass map product was derived based on based on direct comparison of image maps to field survey data for the relevant seagrass and environmental properties.

7 Further development

In combination with work completed in Phase 1 of the CRC, the project team has built an internationally unique image and field archive data for Moreton Bay which has been processed with new field and image based techniques for mapping benthic cover types, their structural properties and associated environmental properties, including water depth and clarity or quality indicators.

Our current and future works on delivering mapping and monitoring solutions for coastal environments will rely heavily of the data, techniques and skills the project team has developed through the CRC. More specifically, the ongoing applications of our work will be:

- Completion and refinement of the web-based toolkit for mapping coastal environments from remotely sensed data (http://www.coastal.crc.org.au/rstoolkit/index.html). We expect this toolkit to be continually updated as our knowledge, technique, and skill base grow and see it as a repository for our work and as a critical tool for educating groups with which we work. We also expect to use this approach as part of our World Bank GEF Coral Reefs project to communicate the most suitable mapping methods to management agencies in developing countries.
- The image and field data sets collected in Moreton Bay will provide the basis for an international evaluation of the best practice in optically shallow remote sensing methods for depth, water quality and substrate. This project has received funding from The United States Official of Naval Research, The University of Queensland and CSIRO. We are in the process of submitting an ARC Linkage International to support an international workshop were all groups invited will process the Moreton Bay data using their approaches and then validate results. An analysis will then be conducted to determine the most accurate algorithms.
- The field survey techniques that were refined as part of this work have become the basis for a benthic survey manual which we are in the process of working with the Great Barrier Reef Marine Park Authority and the Australian Institute of Marine Science to have adopted as a standard method. We are also working with these groups to develop operational mapping applications to monitor the extent and change in extent of live and dead coral over the entire Great Barrier Reef.
- The image and field data sets collected for this project are unique and will allow a completely new perspective to be taken on seagrass spatial

ecology and physiology. We are in the process of designing projects that will include seagrass physiologists. A key gap in our knowledge is if and how we can use remote sensing for sparse seagrass meadows, and we have just commenced a project with the Reef CRC on that.

- Chris Roelfsema's doctoral research will build on the results presented in this work and further examine the role that different levels of image processing have on the accuracy of benthic cover maps in areas of varying water clarity. This work will be continued in developing countries through the south-west Pacific.
- We would desperately hope to continue the application of the image processing techniques developed in Phase 1 and Phase 2 of our work for monitoring water quality and benthic habitat. Unfortunately there have been very limited opportunities to do so, and we would strongly recommend funding for this type of work given its potential to be used across all levels of government from local to national scales in monitoring and managing coastal environments.

8 Conclusion

Our results have clearly shown how several of the most commonly available types of remotely sensed data sets can be used by scientists and managers to produce accurate spatial information relevant to mapping and monitoring a key biophysical property of coastal habitats. The most detail and highest accuracy in terms of submerged aquatic vegetation species composition, density and biomass was obtained from airborne hyperspectral image data, closely followed by high spatial resolution satellite multispectral image data. Moderate spatial resolution multispectral image data still provided sound results for mapping seagrass density and biomass, but lacked the spatial, spectral and radiometric resolution to deliver more detailed maps. The level of image correction and amount of field data used in the pre-processing and training of mapping algorithm was positively associated with map accuracy.

The primary objective addressed by this project was the production and verification of maps of benthic substrate types (e.g. seagrass, algae, coral, sand or mud) and their biophysical properties for sections of Moreton Bay using airborne and satellite image data sets.

All of the following objectives were met:

(1) To collect, and deliver in a georeferenced GIS, a set of field survey data on seagrass species, density and above-ground biomass for as many sites in Moreton Bay as possible.

(2) To collect and deliver georeferenced, atmospherically and air–water interface corrected airborne hyperspectral (CASI-2) and satellite multispectral (Quickbird-2, Landsat 5 TM) images for Moreton Bay during the same period that field survey data were collected.

(3) To process the corrected image data sets to produce maps of seagrass density, seagrass species composition and above-ground seagrass biomass for specific sections and all of Moreton Bay.

(4) To process the corrected airborne hyperspectral data to map water depth, water quality and substrate cover types.

(5) To estimate and evaluate the accuracy level of each image–seagrass map product based on direct comparison of image maps to field survey data for the relevant seagrass and environmental properties.

The project clearly demonstrate the need for inter-agency collaboration in the collection, processing, analysis, storage and maintenance of spatial data sets that are required by multiple groups and are often too expensive for groups to collect and produce individually.

Highlights:

- Collaboration
- High quality output products
- Capacity for future work

Lowlights:

- Problems with hyperspectral image data collection and processing that slowed the project by 6–8 months.

References

Bukata, R., Jerome, J., Kondratyev, K. & Pozdnyakov, D. (1995) *Optical properties and remote sensing of inland and coastal waters*. 362 pp. CRC Press, Boca Raton.

Congalton, R.G. (1991) A review of assessing the accuracy of classification of remotely sensed data. *Remote Sensing of Environment* 37(1): 35–46.

Dekker, A.G. & Phinn, S. (eds) (2005) *Port Curtis and Fitzroy River Estuary Remote Sensing Tasks*. Coastal CRC Technical Report. 178 pp. CRC for Coastal Zone, Estuary and Waterway Management, Brisbane.

Hyland, S.J., Courtney, A.J. & Butler, C.J. (1989) Distribution of seagrass in the Moreton Region from Noosa to Coolangatta. 42 pp. QDPI Information series: QI89010.

Lee, Z.P., Carder, K.L., Mobley, C.D., Steward, R.G. & Patch, J.S. (1999) Hyperspectral remote sensing for shallow waters: 2. Deriving bottom depths and water properties by optimization. *Applied Optics* 38(18): 3831–3843.

Phinn, S. & Dekker, A.G. (eds) (2004) *An Integrated Remote Sensing Approach for Adaptive Management of Complex Coastal Waters. The Moreton Bay Case Study*. Coastal CRC Technical Report No. 23. 142 pp. CRC for Coastal Zone, Estuary and Waterway Management, Brisbane.

Appendices

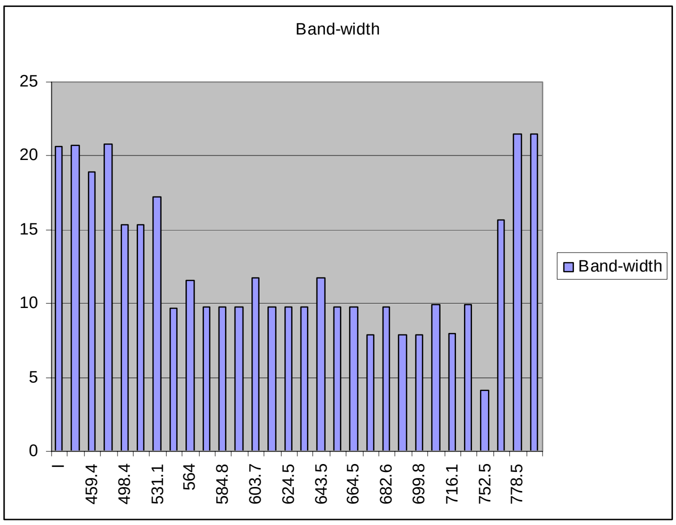
Appendix 1.1 CASI spectral band set

<u>Moreton Bay Coverage—2004</u>

Aquatic band set

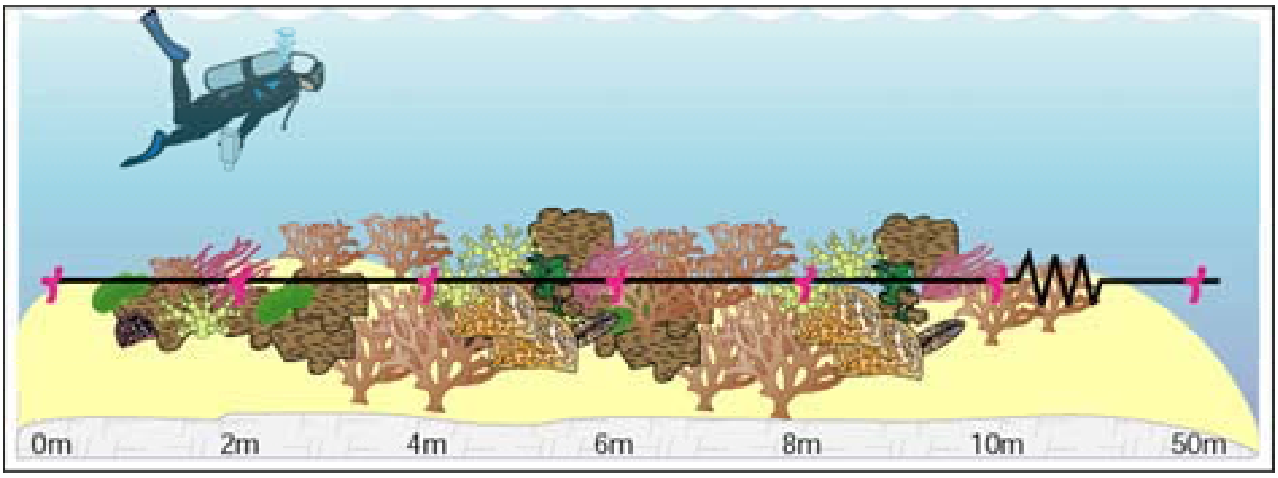
Source: Dekker, A. & Brando, V. (2001) *CASI-2 bandset for Moreton Bay acquisition*, February 2001.

Band no.	λ	Band-width	Min. λ	Max. λ	Features	Sensors
1	439.0	20.6	428.7	448.3	Chl-Ŭ 438 nm max., CDOM, sun glint	MERIS 2
2	459.4	20.7	449.05	468.75	CDOM, chl. ref., sun glint	
3	478.8	18.9	469.35	487.25	CDOM, accessory pigments	
4	498.4	20.8	488	507.8	CDOM, accessory pigments	MERIS 3
5	516.1	15.3	508.45	522.75	MP-SS, TSM	MERIS 4
6	531.1	15.3	523.45	537.75	MP-SS, TSM	
7	547.1	17.2	538.5	554.7	MP-SS, Ref. CPE, TSM	
8	564.0	9.7	559.15	567.85	CPE, TSM	MERIS 5
9	574.4	11.6	568.6	579.2	MP-SS, Ref. CPE, TSM	
10	584.8	9.8	579.9	588.7	MP-SS, TSM	
11	594.2	9.8	589.3	598.1	MP-SS, Ref. CPC, TSM	
12	603.7	9.8	598.8	607.6	MP-SS, Ref .CPC, TSM	
13	614.1	11.7	608.25	618.95	MP-SS, Ref. CPC, TSM	
14	624.5	9.8	619.6	628.4	CPC, TSM	MERIS 6
15	634.0	9.8	629.1	637.9	MP-SS, Ref. CPC, TSM	
16	643.5	9.8	638.6	647.4	MP-SS, Ref. CPC, TSM	
17	654.0	11.7	648.15	658.85	MP-SS, Ref. Chl , TSM	
18	664.5	9.8	659.6	668.4	Chl-Ŭ fluor. algorithm, TSM	MERIS 7
19	674.0	9.8	669.1	677.9	Chl 676 nm max., TSM	
20	682.6	7.9	678.65	685.55	Chl-Ŭ fluor. peak, Chl Ref, TSM	MERIS 8
21	691.2	9.8	686.3	695.1	Chl-Ŭ fluor. peak, Chl Ref, TSM	MERIS 9
22	699.8	7.9	695.85	702.75	Chl-Ŭ fluor. algorithm, Chl Ref, TSM	
23	707.5	7.9	703.55	710.45	Chl-Ŭ fluor. algorithm, Chl Ref, TSM	
24	716.1	9.9	711.15	720.05	Chl-Ŭ fluor. algorithm, TSM	
25	732.4	8.0	728.4	735.4	Mangrove, red edge	
26	752.5	9.9	747.55	756.45	Atm. ref. 761 nm O_2 , sun glint	MERIS 10
27	759.3	4.1	757.25	760.35	761 nm O_2 abs. max., sun glint	MERIS 11
28	778.5	15.7	770.65	785.35	Atm. ref 761 nm O_2, sun glint	MERIS 12
29	866.2	21.5	855.45	875.95	Atm. water vapour ref., sun glint	MERIS 13
30	939.7	21.5	928.95	949.45	Atm. water vapour max., sun glint	



Appendix 1.2 Benthic cover survey manual

Benthic validation photo transect method



Method developed by C. Roelfsema, S. Phinn & K. Joyce

Centre for Remote Sensing & Spatial Information Science

School of Geography, Planning & Architecture

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

University of Queensland

Brisbane, Queensland, AUSTRALIA, 4072

Ph: 61-7-3365-2529

Fax: 61-7-3365-6899

Table of contents

List of figures

Summary

This manual describes the methods for conducting still photo (or video frame) surveys to determine percentage horizontal projective cover (herein referred to as '% cover') and species composition of benthic habitat (e.g. seagrass or coral). The data collected are intended to be used for the analysis of remotely sensed images (airborne and satellite images) of coral reef and seagrass environments.

The following is a brief overview—detailed descriptions of all equipment, software and methods are provided in the following sections.

The method described can be used in the following situations:

1. In-water surveys
   - snorkelling
   - diving
   - reef walking
2. Boating surveys
   - using drop (video or still) camera where GPS is in boat
   - using towed video where GPS is in boat are on float above video.

Personnel requirements:

Field work:

- Two snorkellers or divers (with 'advanced certification')
  - One person to take photos
  - One for placing the transect line (could consider not using transect line).

Processing:

- One person with sufficient knowledge to identify the different classes in the photo.

The snorkelling or diving method could be conducted by one diver/snorkeller if workplace health and safety considerations are in place.

Time needed for one 100 m transect with benthic photos every 2.0 m (51 photos):

- 15-20 minutes for a team of two snorkellers or divers, to deploy a 100 m transect tape, capture photos of tape at 2 m intervals and retrieve tape.

- 1 hour to download and analyse (by a benthic specialist) 51 photos from 100 m transect using CPCE and summarise the results in an Excel graph.

- 10 minutes to link GPS coordinates to analysed photo results and place them on GIS map.

Minimum equipment requirements:

- to get GPS coordinates—handheld downloadable GPS, dry-bag, reel
- to capture photos on transect—survey tape (100 m), basic digital camera in housing with sufficient memory space, battery life, wide-angle lens (recommended), plumb line
- to process GPS coordinates and photos—laptop and software (all sources are listed in Section 1.2). Software to download GPS (free), download camera photos (included in most laptops), analyse video or photo frames (CPCE) (free) and map the results using ArcExplorer (free) or ArcGIS (ArcView) (not free).

Advantages of this approach:

- Information collected is linked to spatial coordinates and therefore it can be related to any georeferenced remote sensing imagery or other spatial data source.
- Photographs are archival and can be analysed in detail to describe or understand results from each photo or more detailed analyses.
- Information can be given about various aspects of the benthos, depending on the detail of the photo and or classification.
- Easy to teach others to conduct the survey and download GPS and photos.
- Analysis can be done by somebody experienced with identifying benthic features.
- Analysis can be done in the field if laptop is available.
- Easy, fast and robust.

- Most of the equipment is used already by most survey teams (e.g. handheld GPS, laptop, digital camera in housing) and does not need extra purchase.
- Software package described are all free except ArcView.
- Coral Point Count Excel Extension is an efficient and a flexible software package for any classification scheme or number of points to be counted on photos.
- Method is flexible can be adjusted for variety of transect length and photo intervals (e.g. 100 m length/ 2 m interval, 20 m length/5 m interval or 25 m length/1 m interval) depending on detail needed. It can also be adjusted for quadrat surveys.
- Compared to video, photos can have higher resolution and are easier to process.

Disadvantages of this approach:

- Analysis of photographs is time-consuming.
- When finished, field survey photos first need to be analysed to determine benthic cover in comparison to in-water assessment of percentage cover.
- No three-dimensional view of benthos, which can create difficulties identifying features.
- Diver can entangle him/herself in line to surface float on GPS.
- For deeper work it still needs two divers.
- Suitable for validating high and moderate spatial resolution imagery but not for low resolution (i.e. pixels > 100 m x 100 m).

Recommended reading

Roelfsema, C.M., Joyce, K. E. & Phinn, S.R. (in press 2005) Evaluation of benthic survey techniques for validating remotely sensed images of coral reefs. *Proceedings 10th International Coral Reef Symposium*. Okinawa.

Hill, J. & Wilkinson, C. (2004) *Methods for Ecological Monitoring of Coral Reefs*. Australian Institute of Marine Science and Reef Check, Townsville.

English, S., Wilkinson, C. & Baker, V. (1997) *Survey Manual for Tropical Marine Resources*. Australian Institute of Marine Science, Townsville.

Oliver, J., Setiasih, N., Marshall, P. & Hansen, L. (2004) *A global protocol for monitoring of coral bleaching*. WorldFish Center and WWF.

1 Equipment Needs

1.1 Hardware

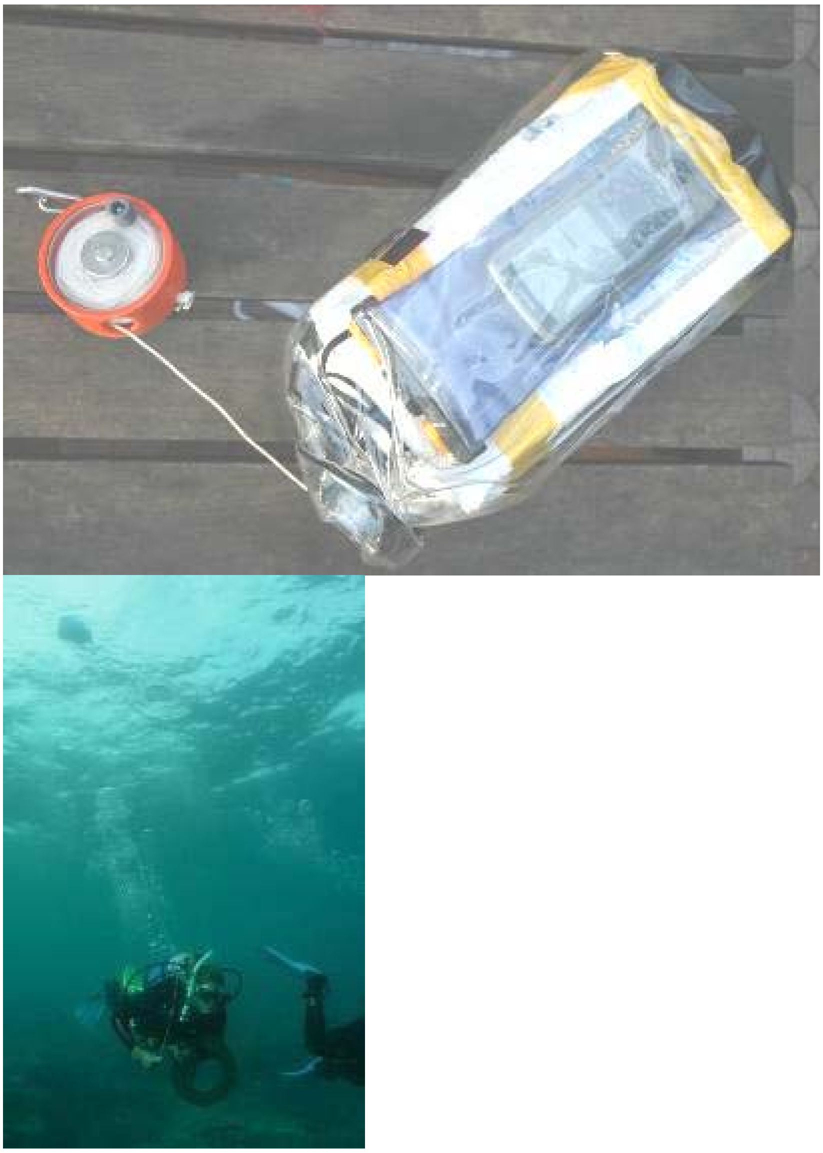
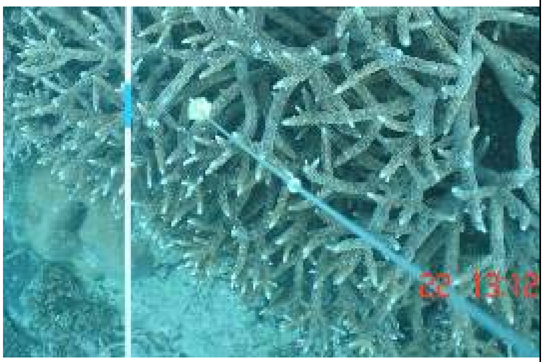


Figure 1a. Dry-bag setup with GPS and reel. Figure 1b. Diver towing GPS and its float.

Equipment	Purpose	Used by UQ	Prerequisites
Digital camera	To take pictures of the substrate	SONY Cybershot PC10 with two batteries and two 256 Mb cards 	Anything equivalent to this which fits in a housing and is easy to handle. Recommended to have sufficient battery life and memory stick; the bigger the better.
Housing for digital camera	Keep the camera dry	Marine-pack housing 	Easy to handle, transparent, not too many buttons stick out, fits in the Boyancy Control Device pocket
Wide-angle lens	Being able to be close to the benthos and photograph a large area	Sea & Sea 16 mm external wide-angle lens 	Wide as possible but still low cost and easy to handle under water. Underwater removable in case other pictures are needed

Plumb line	Have consistent distance from the camera to the bottom to assure same area covered by photograph	Piece of thin line with weight (fishing lead) 	Thin so as not to be obvious in the picture, heavy enough to form a straight plumb line, long enough for the distance needed
Handheld GPS	Logging way points and tracking the surveyor's track	Garmin 72 or 76 Map 	Long battery life, 8 or more channels, up and download capability, logging tracks and waypoints, adjusting logging times (e.g. every 10 secs), adjusting projections and datum
GPS dry-bag	Keeping the GPS unit self extra dry	Aquapack 	Transparent, fits GPS

Float	Needs to keep GPS unit above water surface for most of the time	Any styrofoam or other floating material we can find 	Sufficient floating device to keep GPS at surface
1 kg weight	Needs to hold the GPS in the correct position. Functions as the keel of a boat.	Diver's weight or any other object which makes up 1 kg (e.g. coral rubble) 	Anything that is small and weighs around 1 kg
Dry-bag	Needs to hold the GPS in a small dry back, on top of float with weight.	GMA 	Transparent, waterproof, 10 litres

Small reel	Needs to be connected to float and diver		Reel with thin rope long enough for the working depth of the survey transect, easy to roll up and easy to stop the line from rolling further, small, rope strong enough to pull the float at the surface
Slate	To note and then photograph the begin time, end time, begin depth, end depth, transect direction, date, transect name	Magnadoodle Pro from Fisher Price 	Enough space to write on and easy to wipe out in or underwater and cheap in case of its loss. Magnetic slates are ideal.
Survey tape	100 m tape with 2 m marks on it to mark location of photograph	See photo 	Any survey tape that does not stretch and is easy to roll up. It should have 2 m marks made from electrical tape.

1.2 Software

Software	Purpose	Used by UQ	Prerequisites
Upload/ download GPS	Upload GPS coordinates for transect location and to download tracks and waypoints	Free DNR Garmin extension Program that uploads and downloads from Garmin GPS and converts it to a shapefile directly suitable for ESRI GIS software http://www.dnr.state.mn.us/mis/ gis/tools/ arcview/ extensions/DNRGarmin/ DNRGarmin.html	Any program which can upload to or download from the GPS and translate it into a file format for any GIS package you use
Mapping GIS	To view the downloaded track on an image or map and to check its location	Free ArcExplorer http://www.esri.com/software/arcexplorer/ Works perfectly for just checking track on map or image We mostly use ArcView; you need a licence, but it has more capabilities than only showing the track on a map	
Photo analysis	To determine any characteristics needed for the research (% cover, bottom type, species composition, diseases, sediment colour, algal cover, etc.)	Free CPCE Coral Point Count Excel Extension This program provides an easy way to analyse photos and place results automatically in an Excel spreadsheet http://www.nova.edu/ocean/cpce/	Any other program that is suitable to get the desired information (CPCE is really good)
Download camera photos	To download a camera's photos onto computer	Microsoft Explorer	Any computer these days can download photos from most types of cameras

2 Methods description

2.1 Preparation

1. Place batteries in camera and GPS.
2. Check memory space in camera and GPS.
3. Check projection (e.g. UTM) and datum (e.g. WGS84).
4. Synchronise time of camera, watch and GPS.
5. Set GPS menu on logging track every 5 secs.
6. Set camera menu on best resolution for the detailed needed.
7. Have camera timestamp set on each photo.
8. Place GPS in GPS dry-bag.
9. Place GPS with GPS dry-bag on float so that you can read GPS screen.
10. Place weight on bottom of float.
11. Place weight with float and GPS in big dry-bag.
12. Close big dry-bag and check for leakage.
13. Connect GPS to reel.
14. Enter water with:
    - GPS with float in dry-bag and reel
    - Magnadoodle
    - Camera with plumb line and wide-angle lens
    - 100 m survey tape.

2.2 Step-by-step in water

1. Go to site.
2. Turn on GPS.
3. Take waypoint and note waypoint name.
4. Descend.
5. Roll out tape.

Figure 2. Divers roll out tape

6. Write on slate: site name, start (time, depth), date and possible direction.
7. Take picture of slate.

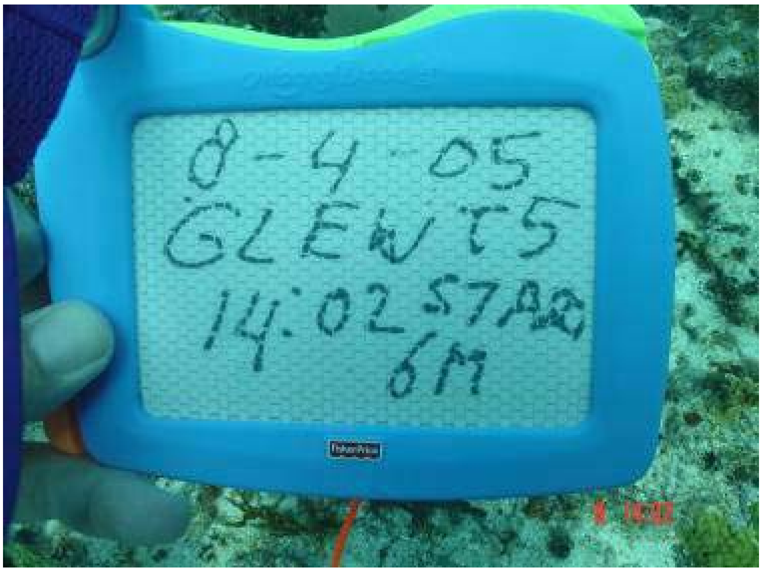


Figure 3. Photo of slate and its data at start of transect

8. Take picture of start of transect 1 m above the bottom (Depending on visibility and detail needed). Use plumb line to get correct distance.


Figure 4. Diver takes photos of benthos and holds reel connected to GPS in hand

9. Repeat this for every 2 m interval until the end of the transect line.

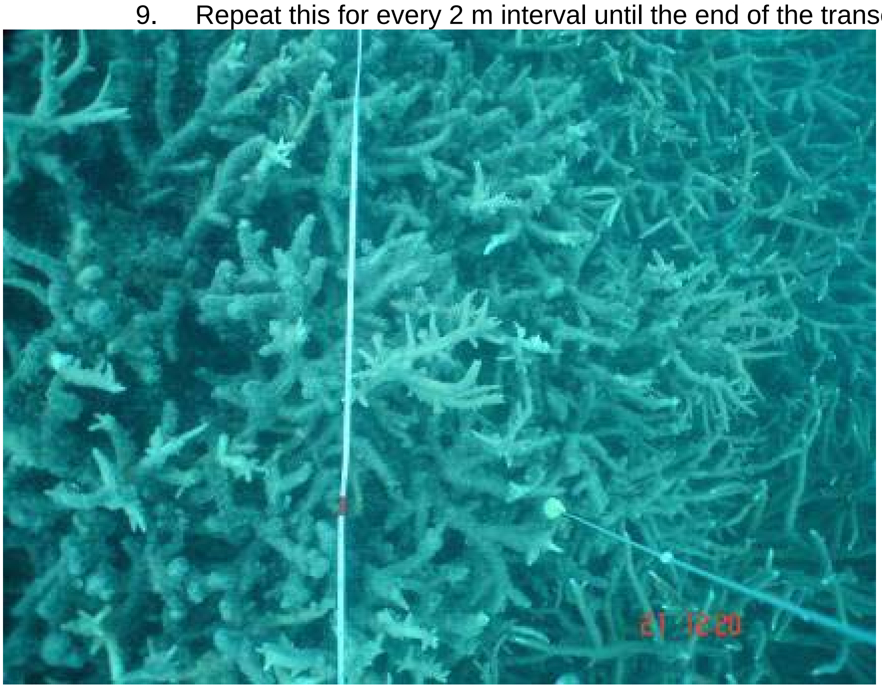


Figure 5. Example photo of benthos, with transect line and 2 m interval marking and plumb line for a set distance from camera to bottom

10. Write on slate: site name, end (time, depth), date, direction.
11. Take picture of slate.

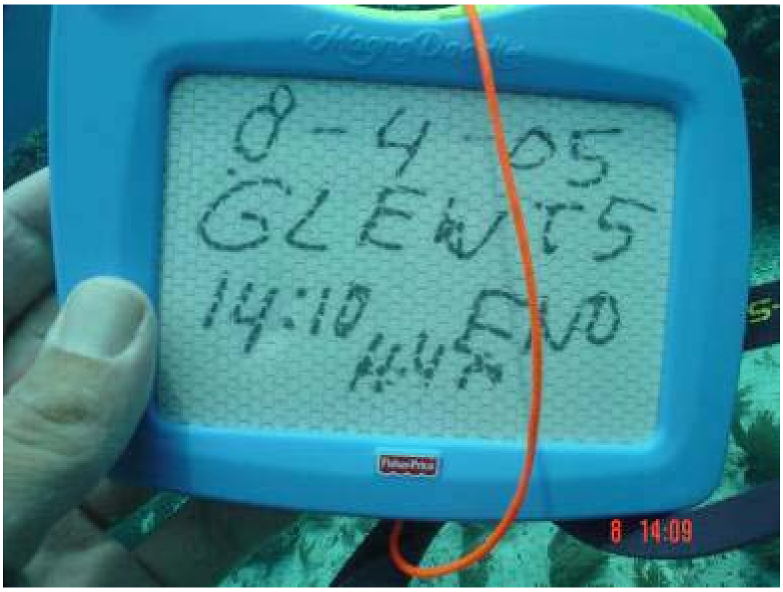


Figure 6. Photo of slate and its data at end of transect

12. Roll up tape.
13. Go to next transect when needed.
14. Ascend/complete dive when finished.
15. Turn off GPS (tracking is stopped then).

2.3 Data processing

1. Download GPS track and save as **yyyymmdd_site_tr_transectno.shp**
2. Download GPS waypoint and save as **yyyymmdd_site_wp_transectno.shp**
3. Download photos and rename photos to **yyyymmdd_site_transectno_photono.jpg**
4. Analyse photos using CPCE software (see CPCE manual for explanation)
   a. Decide on classes that need to be distinguished this needs to be in a .txt file format that is suitable to read by the CPCE program. See appendix for example.
   b. Decide on the number of points per photo which need to be classified.
   c. Select the photos per transect.
   d. Start analysis:
      Select photo and determine the class for each of the points (circle):
      - when circle is green, then class label has been assigned
      - when circle is yellow, current class label has yet to be assigned
      - when circle is red, class has not been assigned.

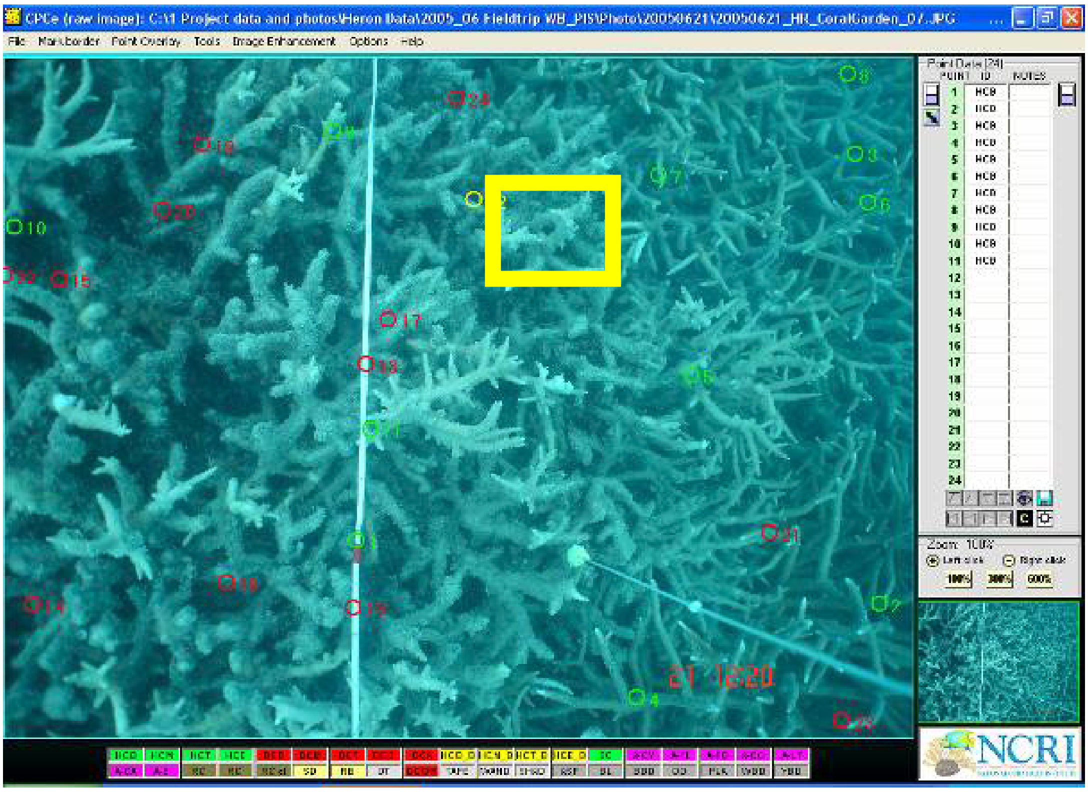


Figure 7. Screen grab of photo analysis CPCE program. Main photo with circles in different colours (green = class assigned, red = class not assigned yet, yellow = class currently assigned). On the right is table with point numbers and its assigned classes. On the bottom the coloured bar represents the different class types that can be assigned.

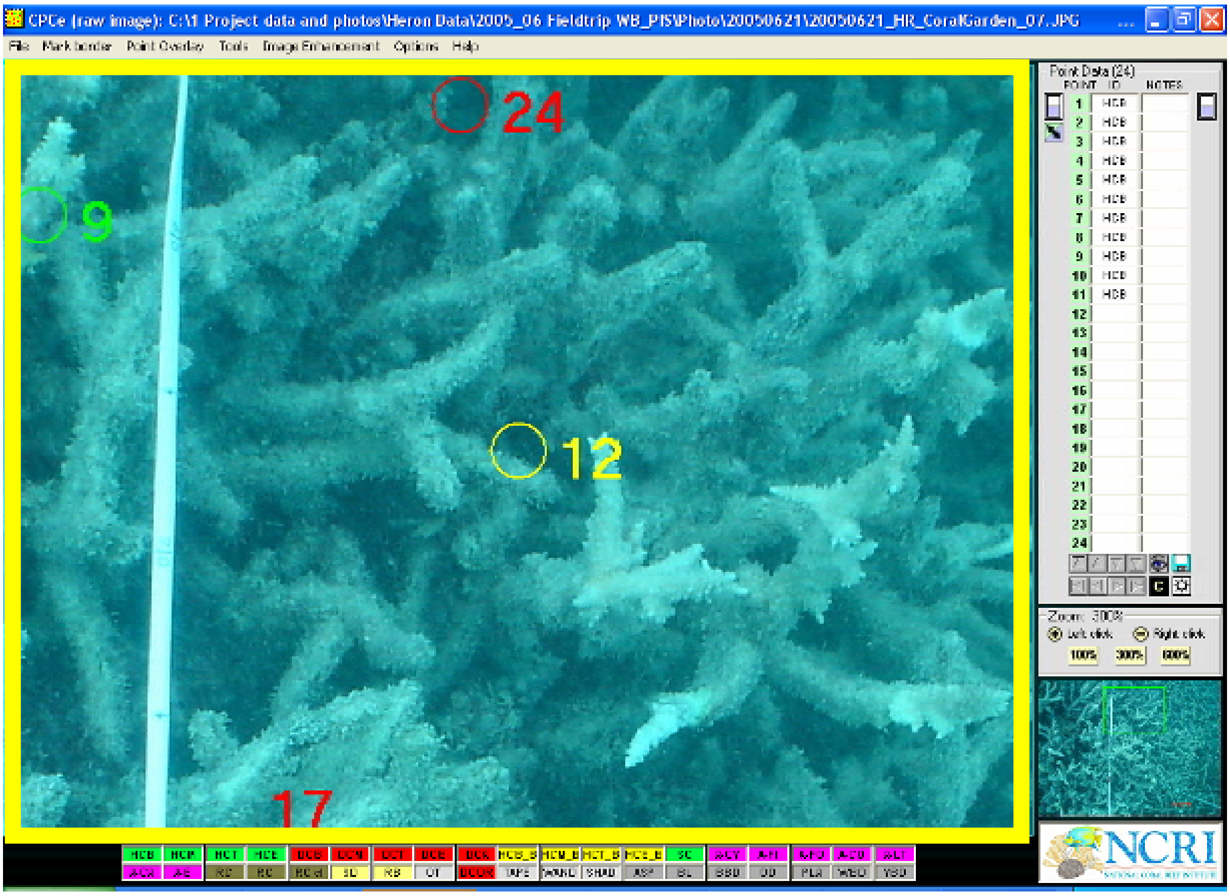


Figure 8. Screen grab of photo analysis CPCE program. Main photo is a zoom-in of the point that needs a class assigned. Circles in different colours (green = class assigned, red = class not assigned yet, yellow = class currently assigned). On the right is table with point numbers and its assigned classes. On the bottom, the coloured bar represents the different class types that can be assigned. Program will automatically jump to next point when point is assigned.

e. Process whole transect to an Excel file and name **yyyymmdd_site_transectno.exl**. This file contains three sheets per transect: (1) raw data per photo, (2) summary report per photo (3) summary report per transect. Summary report contains the calculated percentage for each of the benthic classes and standard deviations.

f. Create graphs of information per photo.

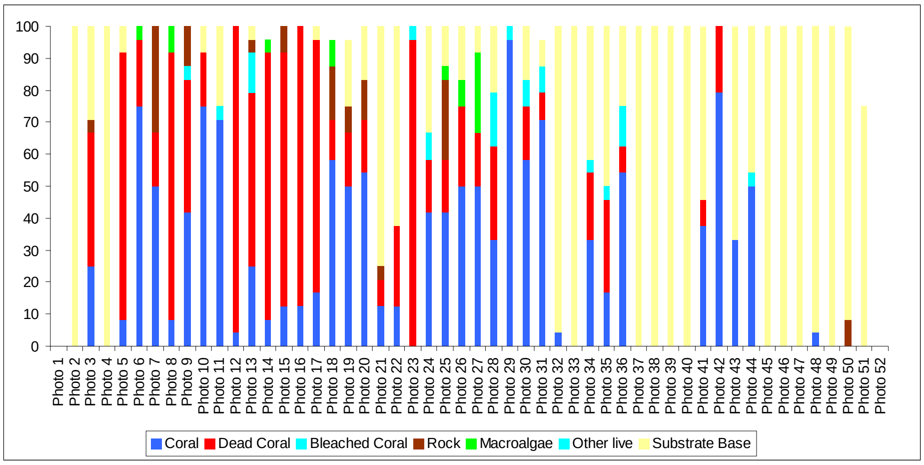


Figure 9. Benthic cover per photo per transect

5. Linking photo data to coordinates
   a. Load GPS transect track in GIS program.

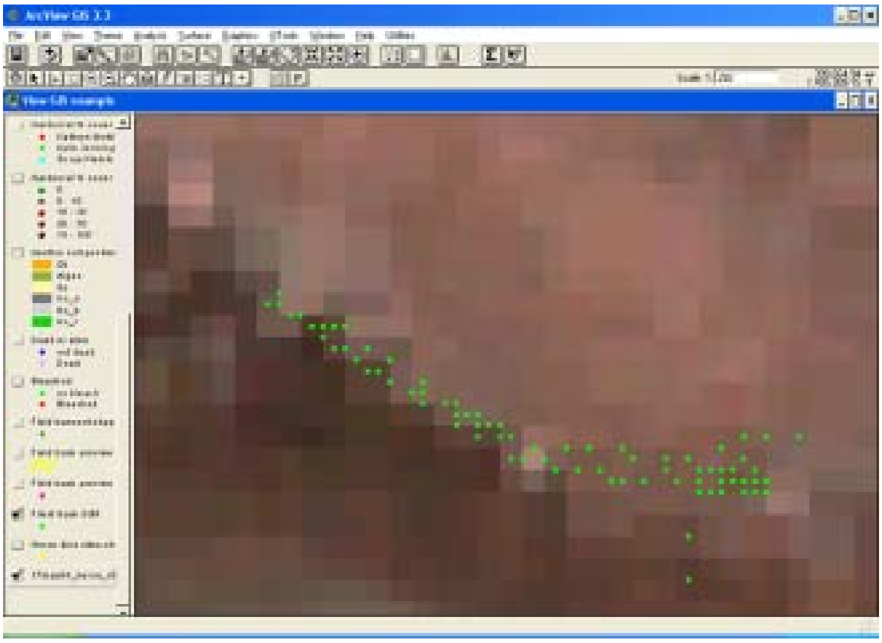


Figure 10. Track of transect on map

   b. Determine from map in the GIS program, the begin, breakpoints and end coordinates of transect.

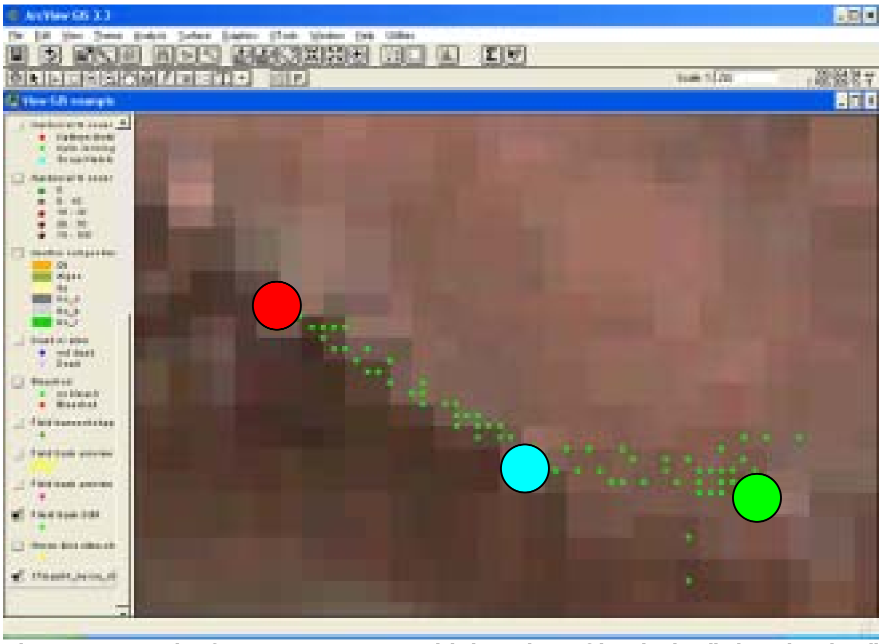


Figure 11. Track of transect on map with location of begin (red), breakpoint (blue) and end point (green)

c. Open **yyyymmdd_site_transectno.exl** in Excel.
d. Add two columns; one for X-coordinate and one for Y-coordinate.
e. Add coordinates for begin, breakpoints and end points for the begin, breakpoint and end photos.
f. Interpolate the coordinates for the photos in between begin, breakpoint and end point.

6. When using ArcView:

g. Save **yyyymmdd_site_transectno.exl** as .dbf file.
h. Import .dbf file in ArcView and save as shapefile.
i. Place results on a map.

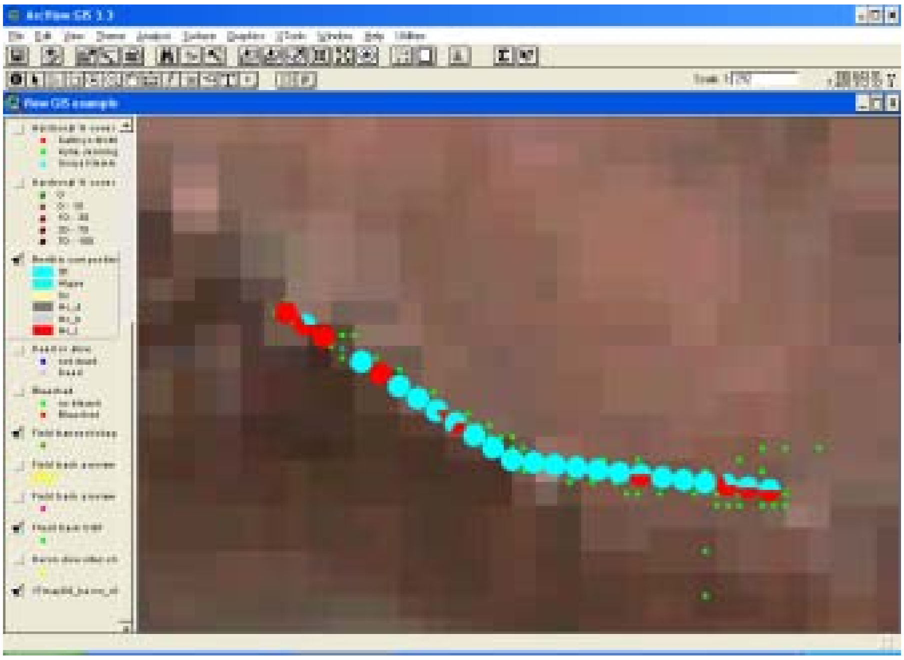


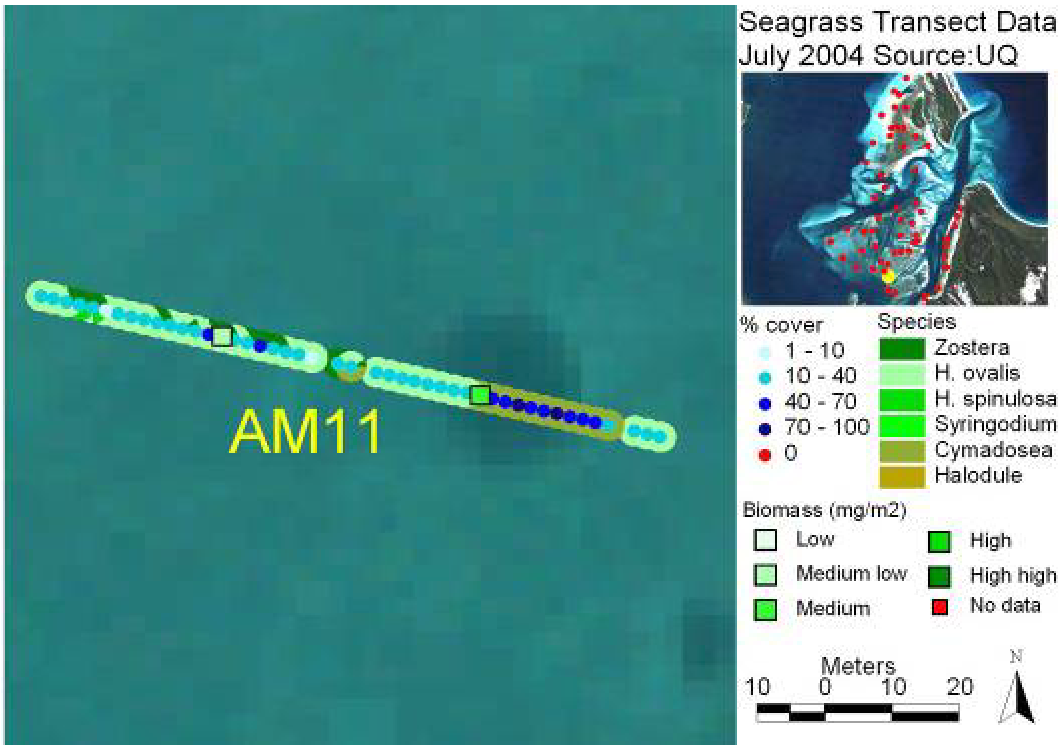
Figure 12. Example of result on map

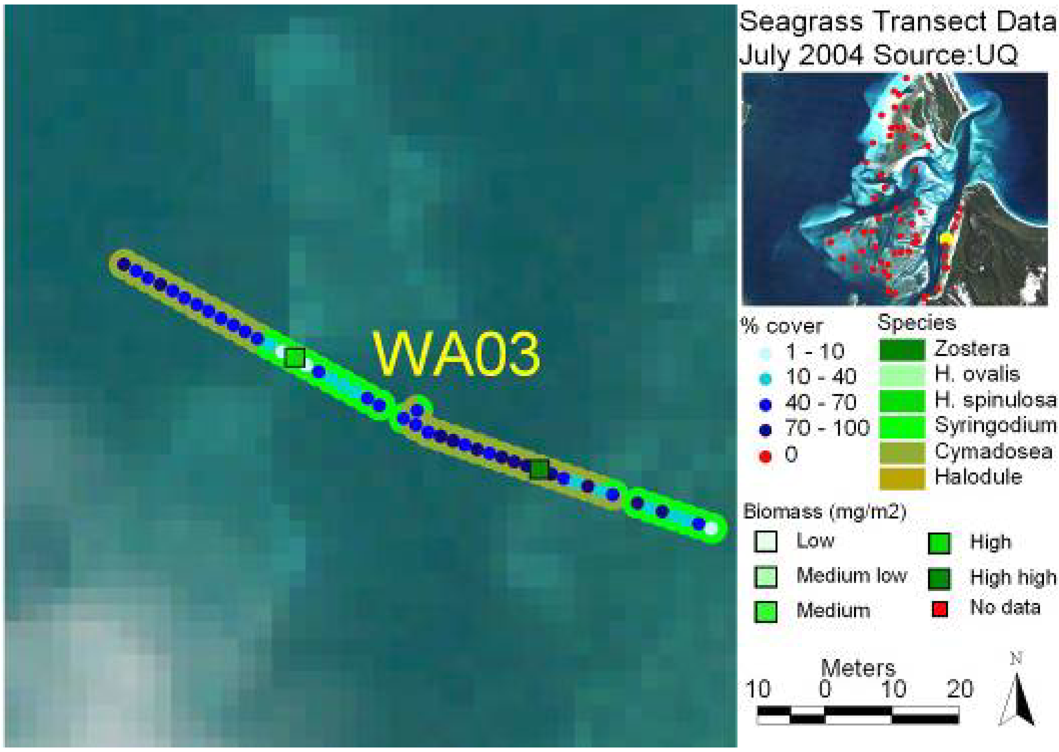
3 Tips

- Download tracks and GPS daily to secure data.
- Check tracks and photos daily to secure quality.
- Check tracks were conducted at planned positions.
- Place desiccant gel packs in dry-bag and inner bag to absorb moisture.
- Check the GPS constellation on dates of planned to survey to ensure there are at least six satellites visible.
- Cool the GPS between dives/snorkels since it can get hot in the dry-bag.
- Have one person analyse photos to ensure consistency in analysis.
- Create metadata file that consists of information on who took the photos, rolled out the line, analysed photos, and downloaded the GPS and photos.
- Camera sometimes fogs on the inside of the housing. By placing camera between surveys in a bucket in the shade, the temperature change is reduced.
- Having sufficient memory space and battery power or having two identical setups can ensure that no batteries or cards need to be changed in the field.
- When aligning field data with image data, the accuracy of the image georeferencing should be similar to that of the field data.
- ArcExplorer cannot be used to add information to each of the points; this has to be done in the .dbf file, which is then transformed to shapefiles.

4 Appendix

4.1 Example results





4.2 CPCE example class file

```
8
"C","Coral"
"DC","Dead Coral"
"BC","Bleached Coral"
"RC", "Rock"
"MA","Macroalgae"
"OL","Other live"
"Su", "Substrate Base"
"TWS","Tape, wand, shadow"
"HCB",  "Hard Coral Branching","C"
"HCM",  "Hard Coral Massive","C"
"HCT",  "Hard Coral Table","C"
"HCE",  "Hard Coral Encrusting","C"
"DCB",  "Dead Coral Branching","DC"
"DCM",  "Dead Coral Massive","DC"
"DCT",  "Dead Coral Table","DC"
"DCE",  "Dead Coral Encrusting","DC"
"DCA",  "Dead coral with algae","DC"
"HCB_B",  "Bleached Hard Coral Branching","BC"
"HCM_B",  "Bleached Hard Coral Massive","BC"
"HCT_B",  "Bleached Hard Coral Table","BC"
"HCE_B",  "Bleached Hard Coral Encrusting","BC"
"SC",  "Soft Coral", "C"
"A-CY", "Cyanobacteria", "MA"
"A-FI", "Filamentous - cladophora", "MA"
"A-FO", "Foliose – Ulva dictyota", "MA"
 "A-CO", "Corticated - Caulerpa", "MA"
"A-LT", "Leathery - Sargassum", "MA"
"A-CA", "Calcareous - Halimeda", "MA"
"A-E", "Crustose – red crustose", "MA"
"RC cor",  "Corraline on rock","RC"
"RC turf",  "Turf on rock","RC"
"RC cl",  "Rock clean","RC"
"SD",  "Sand","Su"
"RB",  "Rubble","Su"
"OT",  "Other","OL"
"DCOR", "Diseased coral","DC"
"TAPE",  "Tape","TWS"
"WAND",  "Wand","TWS"
"SHAD",  "Shadow","TWS"
NOTES,NOTES,NOTES
"ASP",  "Aspergillis","NA"
"BL",  "Bleached coral point","NA"
"BBD",  "Black Band Disease","NA"
"OD",  "Other disease","NA"
"PLA",  "Plague, Type II (White Plague, Type II)","NA"
"WBD",  "White Band Disease","NA"
"YBD",  "Yellow Blotch Disease","NA"
```