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Caractérisation de la résilience des communautés benthiques récifales par analyse d'images à très haute résolution multi-sources: le cas du Parc National de Bunaken, Indonésie

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ACRONYMS

AFD	Agence Française de Développement
ADT	Absolute Dynamic Topography
AVISO	Archiving Validation and Interpretation of Satellite Oceanographic Data Center
BI	Bunaken Island
BNP	Bunaken National Park
CLS	Collecte Localisation Satellite
CTI-CFF	Coral Triangle Initiative on Coral reefs Fisheries and Food security
ENSO	El-Niño Southern Oscillation
GPS	Global Positioning System
ICZM	Integrated Coastal Zone Management
INDESO	Indonesian Development of Space Oceanography
IRD	Institut de Recherche pour le Développement
IUU	Illegal Unreported and Unregulated
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LIT	Line Intersect Transect
MCA	Marine Conservation Area
MMAF	Ministry of Marine Affairs and Fisheries
MSA	Medium Scale Approach
ROI	Region Of Interest
SCUBA	Self Contained Underwater Breathing Apparatus
SLA	Sea Level Anomalies
TS	Transect Station
VHR	Very High spatial Resolution

INTRODUCTION (in French)

L'Indonésie est un ensemble d'archipels regroupant environ 17.500 îles. C'est le pays au monde qui comprend la présence la plus importante de récifs coralliens, actuellement estimée à 50.200 km^2 de zones récifales. Les récifs indonésiens sont réputés pour leur diversité biologique et leur complexité écologique, et sont situés à l'épicentre du centre mondial de la biodiversité marine tropicale, le dit Triangle de Corail (Coral Triangle). Dans ce vaste domaine récifal, la diversité des coraux dépasse 500 espèces qui correspondent à plus de 70% du total des espèces de la zone Indo-Pacifique (Veron, 2000). Cette zone prend également en charge la plus grande diversité de poissons récifaux (Allen et Steene, 1994), et est clairement d'importance mondiale comme l'un des principaux réservoirs de biodiversité marine tropicale (Turak et Devantier, 2003). Malheureusement, une cartographie complète de la géomorphologie ou des habitats des récifs coralliens en Indonésie reste indisponible. Un travail est nécessaire à toutes les échelles en termes de compréhension de l'écologie des récifs coralliens indonésiens.

Le projet INDESO (Développement de l'Océanographie Spatiale en Indonésie) en collaboration entre le gouvernement indonésien (Ministère des affaires maritimes et des pêches - MMAF) et la société française CLS (Collecte Localisation Satellite) promeut l'utilisation des technologies spatiales pour la surveillance des côtes et des mers indonésiennes. Le projet concerne (1) le développement durable des zones côtières, et (2) la pêche et l'aquaculture. Le premier volet comprend le suivi des récifs coralliens, la gestion intégrée de la zone côtière, les mangroves et la surveillance des rejets d'hydrocarbures. Le second comprend la lutte contre la pêche illégale, le suivi des stocks de poissons, l'élevage de crevettes et d'algues agricoles. Dans le domaine corallien, le projet INDESO vise à contribuer certaines des lacunes, en particulier en ciblant des parcs nationaux qui manquent encore de cartes d'habitats dérivés de la télédétection, et d'information sur la dynamique et la résilience des récifs coralliens. Cette thèse fait partie de ce volet sur la surveillance des récifs coralliens, mené par l'IRD (Institut de Recherche pour le Développement).

Un habitat peut être défini comme une entité spatiale et fonctionnelle, caractérisé par différents paramètres biologiques et abiotiques, à une échelle spatiale spécifique qui dépend du contexte (Galparsoro et al., 2012). Lorsqu'ils sont cartographiés par télédétection, les habitats sont décrits par quatre types de variables qui se réfèrent respectivement à la géomorphologie, l'architecture, la couverture benthique et la taxonomie des espèces structurellement dominantes sur des zones qui peuvent couvrir entre plusieurs mètres carrés et quelques milliers de mètres carrés (Andréfouët, 2014, 2016). Les habitants d'intérêt majeur sont généralement des vertébrés et des invertébrés et la flore, parce qu'ils constituent des ressources écologiques ou des entités fonctionnelles qui doivent être cartographiés pour étudier un processus important ou un élément architectural de l'habitat lui-même (les coraux, les algues, le plancton végétal...). Un habitat récifal est donc explicitement considéré ici comme une structure benthique biophysique tridimensionnelle couvrant au moins quelques dizaines de mètres carrés.

Le panel de méthodes de cartographie de l'habitat à l'aide de la télédétection est vaste (cf. revue dans Andréfouët, 2016). Le type de méthodes dépend de l'approche choisie pour le traitement de l'image (classification, segmentation, basée sur la physique, l'intelligence artificielle, ou un mélange de ces approches), le type de capteur (résolution spatiale et spectrale), la faisabilité de la vérification sur le terrain, et surtout les objectifs de l'application. Des exemples de ces approches appliquées aux récifs coralliens peuvent être trouvés dans Purkis (2005, basé sur la physique), Andréfouët et al. (2003, basé sur la classification), Roelfsema et al. (2013, sur la base de segmentation), et Benfield et al. (2007, classification fondée sur des règles, liées à l'intelligence artificielle), par exemple.

Le choix méthodologique dans cette étude a été dicté par les contraintes spécifiques au projet INDESO et au contexte indonésien. Tout d'abord, la priorité d'INDESO est de développer des projets pilotes utilisant des images multispectrales (4-8 bandes) à très haute résolution spatiale (2-4 mètres). Deuxièmement, les récifs indonésiens étant à l'épicentre de la diversité des récifs coralliens, il est souhaitable d'essayer d'inventorier et de cartographier le plus grand nombre d'habitats, un exercice toujours pas atteint dans le pays. Troisièmement, une activité intense de vérité terrain a été prévue sur les sites pilotes d'INDESO. Quatrièmement, INDESO assure un renforcement des capacités qui doit permettre, dans un avenir à moyen terme, de cartographier le plus grand nombre possible de récifs. La priorité absolue est donc la production de cartes thématiques pertinentes, et non de développer de nouvelles méthodes. Les approches qui nécessitent des compétences techniques limitées, en particulier dans le transfert radiatif physique, doivent être favorisées si elles permettent la production de cartes thématiquement riches des habitats des récifs coralliens.

Dans un article de synthèse, Andréfouët (2008) a fait des recommandations pour répondre exactement à cette demande, la priorité à la production de cartes thématiques riches en utilisant des images de très haute résolution dans un contexte de renforcement des capacités.

La méthodologie qu'il recommande est une « méthodologie de l'utilisateur », dans le sens où l'objectif est de produire des cartes intéressantes pour les utilisateurs et ne pas se concentrer sur les aspects méthodologiques qui peuvent présenter d'abord un intérêt pour les « producteurs ». Les utilisateurs peuvent être des gestionnaires ou des scientifiques qui ont besoin de l'information spatiale sur les habitats, sans pour autant la produire eux-mêmes.

Plusieurs étapes sont nécessaires à l'établissement de cartes par l'utilisateur, dont la description de la typologie de l'habitat, la photo-interprétation des images et l'évaluation de la précision (Andréfouët, 2008). Ensuite, d'autres étapes nécessaires sont liées à l'amélioration de l'image pour la photo-interprétation, la stratégie d'échantillonnage pour les travaux sur le terrain, et enfin le transfert des informations au format des systèmes d'information géographique (SIG). L'évaluation de l'exactitude est une tâche nécessaire dans la cartographie des habitats. Tous ces aspects méthodologiques sont détaillés dans le manuscrit.

Les cartes produites à partir de séries temporelles d'images permettent de répondre à de multiples questions scientifiques, et en particulier de s'intéresser à la résilience des récifs coralliens. La résilience est la capacité d'un système à absorber ou à récupérer de la perturbation et du changement, tout en conservant ses fonctions et services (Carpenter et al., 2001) : par exemple, la capacité d'un récif à récupérer d'un cyclone (Grimsditch et Salm, 2006). Il est souvent opposé à la résistance qui est la capacité d'un écosystème à résister à des perturbations sans subir un décalage de phase ou sans perdre ni sa structure, ni sa fonction (Odum, 1989) : par exemple, la capacité d'un récif à résister au blanchissement et à la mort (Grimsditch et Salm, 2006).

Les questions scientifiques abordées dans ce mémoire peuvent être regroupées en 3 séries de questions et de paliers importants :

1. Quels sont les habitats actuels des récifs coralliens dans le parc national de Bunaken et autour de l'île de Bunaken au nord de Sulawesi ? Comment sont-ils distribués? Quelle est la diversité de l'habitat?

2. Peut-on détecter des changements d'habitats sur une série temporelle d'images multi-capteurs à très haute résolution ? Peut-on reconstruire l'histoire récente de changements autour de l'île Bunaken ? Les habitats sont-ils résilients ?

3. S'il y a des changements d'habitats sur les récifs, quelles peuvent en être les causes ? S'il n'y a pas de changement, quels facteurs de résilience pourraient être impliqués ?

L'objectif principal du travail est donc de déterminer si les habitats des récifs coralliens dans l'île de Bunaken sont résilients, en utilisant i) des cartes d'habitat nouvellement conçues, ii) des données in situ et une série chronologique de 15 ans unique d'images satellites de différents capteurs à très haute résolution (VHR), iii) des données auxiliaires qui pourraient expliquer les changements détectés. En effet, la compréhension de la résilience des habitats du récif corallien est considérée comme une priorité, en particulier pour percevoir les effets des mesures de gestion et de stress.

La thèse comprend 3 grands chapitres, chacun correspondant à une publication distincte. Ces 3 articles sont précédés d'une introduction (Chap. 1), puis d'une présentation détaillée du site et des outils et méthodes employés dans ce travail (Chap. 2). Le Chapitre 3 présente la cartographie détaillée des 175 habitats des récifs coralliens autour de l'île de Bunaken à l'aide d'une image très haute résolution et de données de vérité-terrain recueillies en 2014-2015. Le Chapitre 4 concerne la mortalité du corail observée en Mars 2016 sur plusieurs des habitats identifiés, concomitamment avec la baisse du niveau de la mer drastique en raison du très fort événement El Niño en cours. Enfin, les séries chronologiques de l'imagerie satellitaire à très haute résolution ont été utilisées pour caractériser la dynamique à long terme des habitats des récifs de Bunaken, en particulier sur les platiers peu profonds, entre 2001 et 2015 (Chapitre 5). Une conclusion générale assortie de perspectives et de recommandations constitue le Chapitre 6. Le manuscrit se termine par 4 annexes.

CHAPTER 1. INTRODUCTION

1.1. The INDESO project

Indonesia is an ensemble of archipelagos representing about 17.500 islands spread on a longitudinal gradient spanning more than 4 000 km. Fisheries are a key activity in rural areas and generate considerable local economic transfers (Nontji, 1987). Indonesia living marine resources are highly vulnerable to unregulated illegal fishing, climate change and increasing anthropogenic influences leading to the degradation of marine ecosystems. The management of marine resources and fisheries is therefore highly complex and difficult, and constitutes a major issue for the country.

Since 1999 the Ministry of Marine Affairs and Fisheries (MMAF) established in Indonesia various programs aimed at enhancing the use of remote sensing technology to strenghten the monitoring capacities of the country(Farhan and Lim,2010). In this context, the Infrastructure Development for Space Oceanography project (INDESO) is a scientific program that aims at supplying to the Indonesian MMAF a set of technologies, specific know-how, actions of strengthening of capacities, specific buildings with equipments and facilities. It is funded by an Agence Française de Développement (AFD) sovereign loan of 30 million US$, and the main French partner is Collecte Localisation Satellite (CLS). The long-term objective of INDESO is 1) the conservation of both the capacities of fisheries and of Indonesian ecosystems, 2) the implementation of pilot projects for applied and operational researches and 3) the funding of training actions in the field of space oceanography. The Institute de Recherche pour le Developpement (IRD) is a scientific partner of CLS in INDESO.

INDESO is a mix of operational applications and pilot-research application based on remote sensing and numerical modelling. The program divided into two categories consisting of 7 applications: Sustainable Coastal Development = Coral reef monitoring; Oil spill monitoring; Integrated Coastal Zone Management (ICZM) and Mangrove; Fisheries and Aquaculture especially the detection of Illegal, Unreported and Unregulated (IUU) fishing; Monitoring fish stocks; Shrimp farming; and Seaweed farming. Each of this application has to demonstrate the value of using remote sensing for monitoring and management of Indonesian coastal resources.

This PhD project is a contribution to the Coral Reef Application of the INDESO project. The Coral Reef Application is taking advantage of very high spatial resolution images.

1.2. Coral reefs of Indonesia

Indonesia is the country with the highest presence of coral reefs worldwide, currently estimated at 50.200 km^2 of reefal area although this number needs revision. Indonesia has numerous reef types, including barrier reefs, fringing reefs, and atolls for the main ones (Tomascik et al., 1997). Indonesia coral reefs are renowned for their biological diversity and ecological complexity, and are located at the epicentre of the global centre of tropical marine biodiversity, the so called Coral Triangle, which includes Indonesia, Malaysia, Philippines, Timor Leste, Papua New Guinea and Salomon Islands. Within this broad area, reef-building coral diversity exceeds 500 species which correspond to more than 70% of the total Indo-Pacific species (Veron,2000). This area also supports the highest diversity of reef-associated fishes (Allen and Steene, 1994), and is clearly of global significance as one of the main reservoir of tropical marine biodiversity (Turak and DeVantier, 2003).
Unfortunately, a comprehensive mapping of the geomorphology, or habitats of coral reefs in Indonesia remain unavailable. Much is needed in terms of understanding the ecology of Indonesian coral reefs, at all scales. As such, the INDESO project aims to contribute some of the gaps, in particular on several targeted National Parks that still lack remote sensing derived habitat maps and information on the dynamics and resilience of coral reefs.

1.3. Remote sensing of coral reef habitats and habitat mapping

Generally, a habitat can be defined as a spatial and functional entity characterized by various biological and abiotic parameters, at a specific spatial scale that will depend on the context (Galparsoro et al., 2012). For habitat mapping using remote sensing, habitats are described by four types of variables that refer respectively to geomorphology, architecture, benthic cover and taxonomy of the dominant structurally species for areas that may cover between several square meters to few thousands of square meters (Fig. 1) (Andréfouët, 2014, 2016). The inhabitants of interests are typically vertebrates and invertebrates fauna, and flora, because they are either ecological resources or functional entities that need to be mapped to study an important process, or architectural component of the habitat himself (coral, algae, seagrass...).

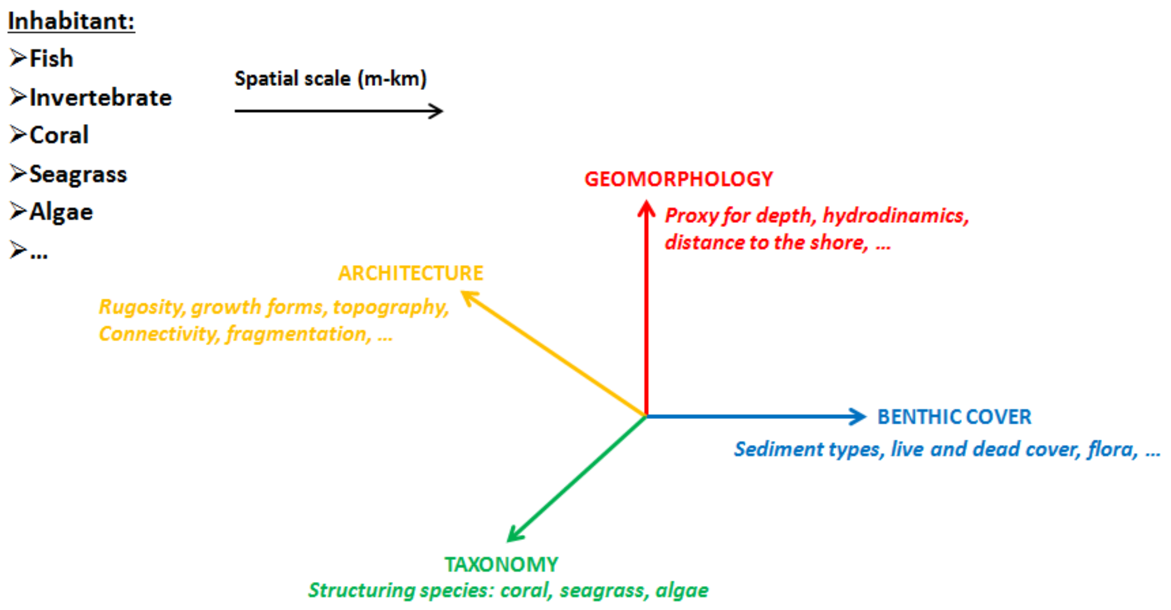

Figure 1: Definition of a habitat in a remote sensing context. A habitat is fully resolved when four variables are explicitly described: geomorphology, architecture, benthic cover and taxonomy (from Andréfouët 2014).

A reef habitat is thus explicitly considered here as a three dimensional benthic biophysical structure covering at least a few tens of square meters.

The geomorphology axis (Fig. 1) is the coarser component. It is a proxy of the depth, physical environment and formation of the location. Often, to map geomorphology, field work and ground-truthing are not necessary. Geomorphology can be mapped directly from the image without field data (Andréfouët et al., 2006). In contrast, the other component of the habitat (cover, architecture and taxonomy) need field investigation to be characterized qualitatively or quantitatively using appropriate field methods that will be presented in Chapter 2. Benthic cover describes how the area is covered by either biotic or abiotic entities. Architecture refers to different information that can be integrative (like the rugosity –or variation of height - of the habitat) or component specific (like the growth form of corals – tabular, massive, branching, etc., or the height of the canopy of an algal bed). Architecture can also refer, at another level, on the spatial topology of the components of the habitat, like patchiness or degree of fragmentation for instance. Examples of representative reef habitats are provided hereafter (Fig. 2) and details of their description are provided in Table 1.

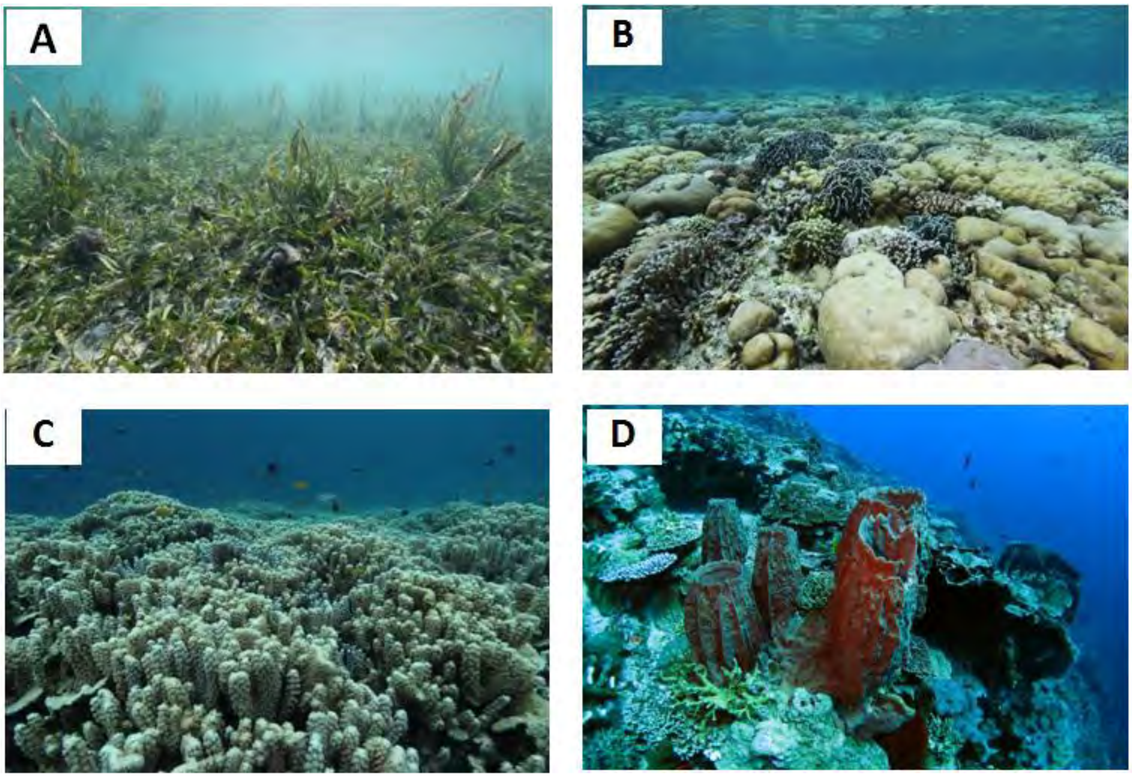

Figure 2: Examples of Indonesian reef habitats, described in Table 1.

Table 1: Detail of definition of reef habitats illustrated in Figure 2

	Geomorphology	Benthic cover	Architecture	Taxonomy
A	Terrace	90% seagrass and 10% sand	Rugosity 2: canopy height 40cm maximum	*Enhalus, Thalassia*
B	Reef flat	80% hard coral, 20% rubble	Rugosity 3: colony height variation below 40cm, flat area. Massive colonies.	*Porites, Pocillopora, Stylophora,* and *Heliopora*
C	Fore reef	100% hard coral	Rugosity 3: slopping area with colony height variation below 40cm. Semi-massive colonies	*Galaxea*
D	Wall	30% sponge, 50% hard coral, 20% old eroded coral substrate	Rugosity 4: steep slope with height variation of components near 100cm. Barrel sponges. Mixed coral growth forms	Sponge: *Xestospongia* Hard Coral: *Acropora, Pectinia, Porites, Isopora, Mycedium*

The panel of methods for habitat mapping using remote sensing is vast (reviewed in Andréfouët, 2016). Only optical images (blue to red wavelength) have been used to study underwater features. Radar images, or near-infra red bands, which are useful to study

vegetation, cannot be used for underwater targets, although they can be used to create a land mask.
The type of methods depends on the selected approach for image processing (classification, segmentation, physics-based, artificial intelligence, or a mix of these approaches), the type of sensor (spatial and spectral resolution), the feasibility of ground-truthing, and, most importantly the objectives of the mapping. Examples of these approaches applied to coral reefs can be found inPurkis (2005, physics-based), Andréfouët et al. (2003, classification-based) and Roelfsema et al. (2013, segmentation based), and Benfield et al. (2007, rule-based classification, related to artificial intelligence) for instance. Here, we can narrow the scope considering several constraints which are specific to the INDESO and Indonesia context briefly explained in the previous sections.

First, the priority of INDESO is to develop pilot projects using very high spatial resolution (2-4 meter), multispectral (4-8 bands), images. Second, Indonesian reefs being in the epicentre of the coral reef diversity, it is desirable to try to inventory and map the highest number of habitats, an exercise still not achieved in for this country. Third, it is expected that intensive ground-truthing is possible for the pilot INDESO sites. Fourth, INDESO is about capacity building so that as many reefs as possible can be mapped in the future. The ultimate priority is thus production of thematically relevant maps, not method development. Approaches that require limited technical skills, especially in radiative transfer physics, should be favoured, if they allow the production of thematically rich coral reef habitat maps.

In a review paper, Andréfouët (2008) has made recommendations for exactly the context presented above: priority to production of thematically rich maps using very high spatial resolution images in a capacity building context. The methodology he recommends is a “user’ methodology, in the sense that the goal is to produce maps interesting for users and not focus on methodological aspects that can be of interest for map “producers”, but not users. Users can be managers, or scientists that need spatial information on habitats, but cannot produce it themselves.

A methodological flow chart was provided in Andréfouët (2008) (Fig. 3). The user and producer flow chart are compared. The user flow chart is simpler but still has several mandatory steps. The three main ones thematically speaking are the description of **habitat typology (step 6),** the **photo-interpretation** of the images (steps 7 – 8) and the **accuracy**

assessment(step 10 (Andréfouët, 2008). Then, other steps are required and are related to image enhancement for photo-interpretation, sampling strategy for field work, and finally transfer into Geographical Information Systems (GIS) format.

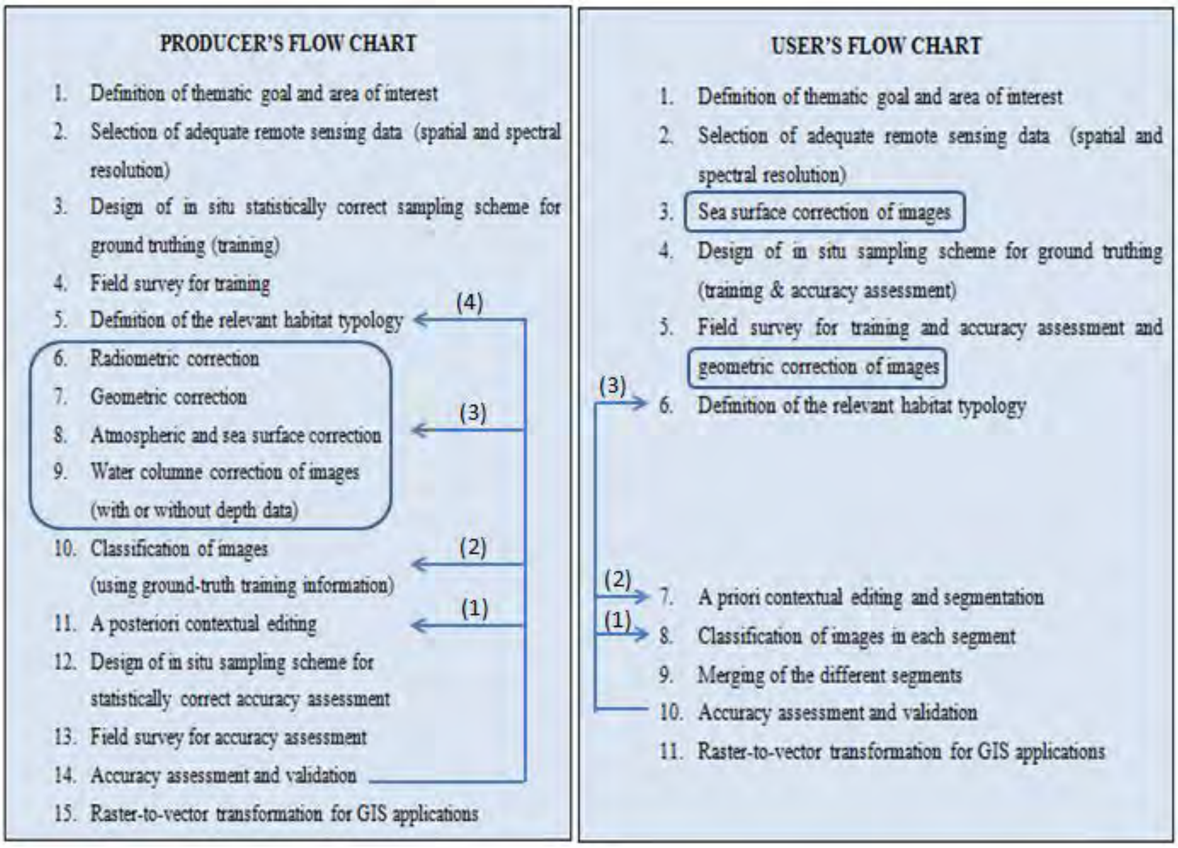

Figure 3: Producers and users flow charts. Items in grey boxes show steps independent of the thematic scope. Arrows point to most frequent need of iterations to enhance accuracy and frequency of actions (1, 2, 3, 4). From Andréfouët (2008)

Accuracy assessment is a necessary task in habitat mapping. The goal is to provide a quantification of the accuracy of the map, which is key information for all users. Many metrics exist (Foody, 2002) that require a set of observations independent from the set of observations used to take the map. (Congalton and Green, 1999) make recommendations in term of sampling effort, with 50 independent points per class for a robust assessment. However, in a coral reef context, this may not be easily feasible, and these guidelines need to be considered as guidelines only, not mandatory. Collecting 50 points per class may be impractical because some classes may be rare with limited coverage, or simply not enough time is allowed in the type of short expedition survey typically done for coral reefs. For a 50-classes map, collecting 500 points may be a costly dedicated full-week task in the field. More importantly it is also very easy to bias accuracy assessment, either positively or negatively depending on where the control points are selected (Andréfouët, 2008). Overall, it is acknowledged that a good accuracy is above 80% overall accuracy, meaning that 80% of all pixels are correctly classified. It also means that 20% of the pixels are mislabelled, which may still be inacceptable for some applications. Therefore, some applications may require values above 90%, if the map is used for precise management of resource stocks for instance. Most of the time, the level of accuracy is highly variable between classes, and overall accuracy is just an indicator that needs to be refined by other metrics provided per classes.

Generally, automatic methods (classification, segmentation) alone cannot reach this level of accuracy for more than 5 or 6 classes in a coral reef environment (Capolsini et al., 2003, Andréfouët et al., 2003). This is due to the inherent radiometric similarity between coral reef benthic classes, such as coral and algae (Hochberg et al., 2003). Higher complexity maps need to be manually edited, by contextual editing (Groom et al.,1996). This means that generic contextual rules (e.g., ‘seagrass are not on the forereef’) can be used *a posteriori* to detect misclassification and correct them. In practice, implementing automatically these rules is complex (with methods related to the field of artificial intelligence and automatic learning). Some software (e.g., Definiens) can be helpful (Benfield et al. 2007) or it is done manually by photo-interpretation (Andréfouët, 2008). Although this is site-complexity dependent, the trend is that aiming for a high accuracy for a high number of classes require lots of editing. As a result, direct photo-interpretation and manual digitization, which is in practice*a priori* contextual editing, is preferred as the main method to produce a map. Photo-interpretation has allowed good level of overall accuracy (>75%) for maps reaching more than 50 classes.

1.4. Remote sensing of Indonesian coral reefs

Indonesia has vast areas of coral reefs, and published remote sensing studies describe imageprocessing in several localities. Covering the entire country, national initiative included a COREMAP product derived for Landsat 7 images (2004). The Millennium Mapping Project has released some detailed geomorphological products (Andréfouët et al., 2006), also derived from Landsat 7, after the 2004 Tsunami. Comparison with COREMAP products showed many missing reefs and errors in the COREMAP product (Brian Long and Serge Andréfouët, unpublished data). The fully validated Millennium product is not yet distributed and a simplified, unvalidated version of the Indonesian products have been used by UNEP-WCMC to release a global “coral reef” product in one single layer without thematical detail. This product also suffers from many errors (Cros et al., 2014). The Table 2 provides recent high spatial resolution studies on Indonesian coral reefs published in the peer-reviewed literature. Other studies can be found in conference proceedings and student thesis. These studies represent a variety of coral reef theme, including change detection (Table 2). These studies looked at SPOT and Landsat imagery, thus analysed changes using 20-30 meter resolution. We did not find example of change detection study using very high spatial resolution images (2-4 m).

1.5. Resilience of coral reefs and mapping resilience

Resilience is the ability of a system to absorb or recover from disturbance and change, while maintaining its functions and services (Carpenter et al., 2001): for example a coral reef 's ability to recover from a hurricane(Grimsditch and Salm, 2006). It is often opposed to resistance, which is the ability of an ecosystem to withstand disturbance without undergoing a phase shift or losing neither structure nor function (Odum, 1989): for example a coral reef 's ability to withstand bleaching and mortality (Grimsditch and Salm, 2006).

Resilience and the resilience concept have been a significant focus in the past 20 years, triggered by the on-going, obvious, degradation of corals reefs that seemed to be unable to bounce back to their initial state, or even shift to a seemingly different system, for instance dominated by algae. Understanding resilience and managing the resilience capacities of a reef have appeared as new priorities for science and management. The difficulty is that managing resilience implies a holistic, ecosystem, view of how a reef is functioning and the consequences of all interactions between all its diversity of components.

Resilience of coral reefs has been studied as a theoretical concept (Nyström and Folke, 2001), empirically in the field (e.g., Wakeford et al., 2008), and with models (Mumby et al., 2006). Resilience has three critical components (1) biodiversity, (2) connectivity and (3) spatial heterogeneity (Nyström et al., 2008). Biodiversity allows redundancy of important ecosystem functions. Connectivity between reefs allows population flux and population renewal after disturbances. Spatial heterogeneity implies that the resilience factors are variable in space across a reef or series of reef. It is recognized that habitat diversity, connectivity and spatial heterogeneity are important resilience modulators, yet these variables remain poorly quantified for most reefs worlwide.

Table 2: List of representative coral reef remote sensing applications in Indonesia

Reference	Location	Type of images	Objective	Period	Method
Newman et al., 2007	Bunaken island	IKONOS	Coral cover and effect of management	07/07/2001 and 06/06/04	Classification, in-situ (transect, ground observation point)
Manessa et al., 2014	Gilis, Lombok	Worldview-2	Habitat mapping	25/01/2010	Lyzenga's methods & in-situ observation (manta tow)
Bertels et al., 2008	Fordata , Nukaha island, Tanimbar	CASI-550	Habitat mapping	01/09/2005	Classification and in-situ observation
Holden, 2002	Bunaken Island	In situ	Characteristic of water quality	07/2000	Water column correction & in-situ observation
Wahiddin et al., 2014	Morotai	Landsat TM, ETM+, OLI	Change detection	30/07/1996, 23/07/2002, 17/10/2013	Classification & water column correction
Holden, 2002	Bunaken Island	SPOT	Habitat mapping	30/06 - 31/07 1994	Maximum Getis Statistic
Holden et al., 2001	Bunaken Island	SPOT HRV	Change detection	08/1997 and 07/2000	Getis Statistic, spatial autocorrelation
Madden et al., 2013	Wakatobi	Landsat 7	Classification of sediments	02/2009	Modern carbonate system
Sawayama et al., 2015	Spermonde	Worldview-2	Fish-habitat relationships	09/2012	Remote sensing approach with underwater visual fish observations
Torres-Pulliza et al., 2013	Lesser Sunda Ecoregion	Landsat 7	Seagrass mapping	1993 & 2003	ISODATA classification, Marxan software & in-situ data.
Kakuta et al., 2010	East Asia	ALOS AVNIR-2	Coral reef distribution	1500 scenes	ISODATA classification

While there is a general consensus on all the factors, from local to global, that can affect coral reef resilience (McClanahan et al., 2012), which factors are the most important for any given reef remains poorly understood (Obura and Grimsdith, 2009). Some modelling studies suggest universal recipes to manage resilience (e.g., the management of herbivores to limit algal overgrowth), but empirical evidences suggest that these recipes cannot cover the range of situation (e.g., Carassou et al., 2013). Models remain invalidated, non-spatial, with arguable parameterization, and the related sensitivity studies can only show the importance of the pre-selected parameters, not those who have been dismissed or neglected. In practice, little is known on what factors contribute to the resilience of coral reef communities and habitats for a particular reef, before it can be studied intensively.

Considering the most likely factors of resilience, remote sensing has been used to map variables that can affect resilience (Table 3). Both stressors and factors of recovery can be mapped and combined in these approaches. A combined index is then used to define areas prone to resilience or not. This is a fairly pragmatic and common-sense approach that could serve well management due to its spatially-explicit approach, yet it remains also very difficult to validate.

Table 3: Examples of variables relevant to measure resilience and mapped or modelled using remote sensing.

Reference	**Variables computed using remote sensing images or modelled using a combination of remote sensing images and *in situ* data**
Rowlands et al. (2012)	1. Live coral abundance 2. Framework abundance 3. Water depth variability (rugosity)
Knudby et al.(2013)	1. Substrate 2. Geomorphology 3. Depth 4. Coral cover 5. Habitat richness 6. Distance to mangroves and seagrass 7. Stress tolerant coral taxa 8. Coral generic diversity 9. Fish herbivore biomass 10. Fish herbivore functional group richness 11. Density of juvenile corals 12. Cover of live coral & crustose coralline algae

Another use of remote sensing to characterize resilience is based on revisiting the history of a reef using time-series of images. This is somewhat in opposition to the modelling-forecasting approach but it is even more interesting, because it can actually show if a reef has been resilient or not after some disturbances, and at which time-scale resilience can be observed. Revisiting the history of reefs can be useful to understand which factors have been at played. However, this approach ideally requires historical field data that are often missing. It is also practically limited to shallow areas. This aspect is the focus of the next section.

1.6. Change detection of coral reefs using remote sensing

Habitat mapping is a one-time mapping exercise, but scientists and managers may also want to know how a reef has changed, and if the habitats are stable, degrading, or enhancing in quality. Change detection of habitats using remote sensing has been the subject of several papers, but far less than habitat mapping. Table 4reviews the characteristics of representative studies, published in peer-review journals, and focussing on coral habitats (not on seagrass habitats).

We found methodological papers that look at correction of images, quantify noise, and test various methods of analysis and correction, sometimes using only one pair of images. There are also a number of thematic papers that have tried to understand and explain the causes of the changes that have occurred on a reef, sometimes across several decades and using up to a dozen of images. Various types of images have been used, including aerial photographs (color and black and white) which allow very long time-series, and sometimes with the analysis of multi-sensor series of images. All study sites were shallow, in less than 10 meter deep at the maximum.

The characteristics of change detection analysis, especially for long periods spanning several decades is that the accuracy of the treatment is often difficult to quantify (Scopélitis et al., 2009). Often, no historical data exists to be able to quantify accuracy with a confidence similar to a present-time habitat mapping exercise. Many areas may remain undocumented, hence the level of analysis may be limited to some variables of the habitat that can be photo-interpreted (geomorphology) or related to known unambiguous spectral signatures (cover) while the other variables remain unavailable without historical surveys (architecture, taxonomy).

Table 4: Examples of coral reef change detection study and their characteristics. PIF: pseudo-invariant features. LIT: Line intersect transect (English et al., 1994). MSA: Medium Scale Approach (Clua et al., 2006).

Reference	Location	Type of images	Objective	Period	Method
Yamano et al. (2000)	Kabira Reef, Japan	Aerial photographs	Habitat changes	1973 - 1994	Photo-interpretation and in-situ observation
Andréfouët et al. (2001)	Carysfort Reef, Florida, USA	Landsat 7 ETM+	Methodological	05/02-27/05 2000	Noise characterization after atmospheric condition & empirical correction
Palandro et al. (2003)	Carysfort Reef, Florida	IKONOS and color aerial photographs	Coral mortality	1981, 1992, 2000	Supervised classification & in-situ observations
Elvidge et al. (2004)	Keppel island (Great Barrier Reef), Australia	IKONOS	Coral bleaching	2001, 2002	Correction based on PIFs, image differences, video-transects observations
Houk & vanWoesik (2008)	Saipan Northern Mariana Islands	Aerial photograph, IKONOS	Habitat changes	1940, 2004	Historical map, present time photo-interpretation and classification, compared with habitat detection by moving window analysis (MWA) on video-transects
Palandro et al. (2008)	Florida Keys, USA	Landsat TM, ETM+	Habitat changes	1984 - 2002	Supervised classification & in-situ observations
Rowlands et al. (2008)	Roatan, Honduras	IKONOS & Quickbird	Methodological, Coral bleaching	2000 - 2005	Empirical correction based on PIFs, atmospheric correction, spectral analysis, in situ observations
Scopélitis et al. (2009)	Saint Leu-Reef, La Réunion	Aerial photographs & Quickbird	Habitat changes	35 years (1973 - 2006)	Photo-interpretation & in-situ MSA
Scopélitis et al. (2010)	Aboré reef, New Caledonia	IKONOS & Quickbird	Habitat changes	2002, 2004	Photo-interpretation & in-situ LITand MSA
Scopélitis et al. (2011)	Heron island, Australia	Aerial photographs & Quickbird	Coral growth	35 years (1972 – 2007)	Empirical correction and classification & in-situ (LIT)
Andréfouët et al. (2013)	Toliara, Madagascar	Aerial photographs, Quickbird & Landsat	Loss of coral habitats	50 years (1962 - 2011)	Correction based on PIFs, photo-interpretation
El-Askary et al. (2014)	Hurghada, Egypt	Landsat TM, ETM+, OLI	Habitat changes	1987, 2013	Supervised classification
Saunders et al. (2015)	Roviana Lagoon, Salomon island	High-spatial resolution pan-sharpened satellite imagery	Coral growth	2003, 2006, 2009, 2012	Photo-interpretation and in situ observations
Nurjannah et al. (2015)	Spermonde, Indonesia	Landsat TM, ETM+, OLI	Coral loss	1972 – 2013	Unsupervised classification

High thematic richness could be achieved by Scopélitis et al. (2009) even with limited ground-truthing, at least to the point that they could demonstrate, using photo-interpretation techniques that an assemblage of coral communities at Saint-Leu fringing reef in La Reunion has recovered after a hurricane and moderate bleaching event across a 35-year period. In contrast, also using photo-interpretation techniques, Andréfouët et al. (2013) showed for the barrier reef of Toliara in Madagascar that coral communities have steadily decreased due to destructive artisanal fishing, without any signs of recovery. These two Indian Ocean stories highlight two different conclusions in term of resilience: based in the trajectory of their coral habitats, Saint-Leu has been a resilient reef in the face of acute short term disturbance while Toliora appears to be a non-resilient reef in the face of chronic disturbance. Thus, time-series of remote sensing images have the potential to inform on the capacity of a reef to be resilient depending on the type of disturbances the reef had to face during the study period.

1.7. General research objective& research questions

The objective of the study is to study for the first time the resilience of an Indonesian coral reef and its habitats, using a multi-sensor time-series of very high spatial resolution (VHR) multispectral satellite images. Bunaken Island, in the Bunaken National park in North Sulawesi, is the study area.

The focus is on thematic interpretation, not image processing method development because the goal is also to provide practical recommendations for Park managers in term of using remote sensing to monitor reefs more effectively, especially the shallow reef flats which have been neglected by monitoring programs.

The INDESO project provides the imagery by purchasing all cloud free images available from the IKONOS, Quickbird, Geoeye and Worldview multispectral archive of images between 2001 and 2015.

The thesis can be divided in 3 series of important questions and steps, inspired by the information presented throughout the previous sections:

1. What are the present day coral reef habitats found in Bunaken National Park and Bunaken Island? How are they distributed? What is the habitat diversity?

2. Can we detect changes in these habitats using a multi-sensor time-series VHR images? Can we reconstruct the recent history of changes around Bunaken Island? Are the habitats resilient?
3. If there are changes on reef habitats after answering Question 2, what are the causes of these changes? If there are no changes after answering Question 2, what resilience factors could be at play?

After answering these questions specific to Bunaken Island, the potential for generalization to other reefs and practical recommendations for mapping and monitoring Indonesian reefs will be discussed.

1.8. Thesis structure

This thesis has been divided into six chapters. Three of them are presented in the form of submitted papers to peer-reviewed journal. We refer to a multi-source approach in the title considering first the use of images acquired by different satellite vectors, but also the use of in situ data, and also the use of altimetry data to explain some of the observed changes.
The current Chapter 1 has presented here the research background and key information used to define the subject, with brief presentation on the INDESO project, Indonesia coral reefs, remote sensing of coral reefs and habitat mapping, remote sensing of Indonesia coral reefs, resilience of coral reefs and its mapping, and change detection of coral reefs. Then the general research objectives and the main research questions are given.
Chapter 2 presents in more detail the field and image processing methods used in the following chapters, and justify the choice of these methods. Bunaken National Park and island are also presented.
Chapter 3 presents the results of the field survey, the creation of a detailed habitat map and the analysis of the map in term of habitat richness and distribution. The chapter is a paper entitled *Revisiting Bunaken Island (Indonesia): a habitat stand point using very high spatial resolution remotely sensed,* which is submitted to the journal Marine Pollution Bulletin, for a special issue on the project INDESO.
Chapter 4 addresses the mortality of corals related to the 2015-2016 El-Niño that we could witness during the study period. This was an opportunistic event that brought new insights on the processes that control the resilience of Bunaken Island coral reef flats. This chapter is a paper entitled *Coral mortality induced by the 2015-2016 El Niño in Indonesia: the effect of*

rapid sea level fall, which is in press with the journal Biogeosciences and also available as a discussion paper open to comments (DOI:10.5194/bg-2016-375).

Chapter 5 presents the change detection analysis of coral reef habitats in Bunaken National Park using an original scenario-based approach. This chapter is a paper entitled *Assessment of the resilience of Bunaken Island coral reefs using 15 years of very high spatial resolution satellite images: a kaleidoscope of habitat trajectorie*s, which is under review with the journal Marine Pollution Bulletin, for a special issue on the project INDESO.

Chapter 6 reviews the results, highlight the main findings and put them in the broader context of understanding the resilience of coral reefs, especially in Indonesia, and make suggestions for the future monitoring of these reefs using a combined remote sensing and monitoring approach.

CHAPTER 2. SETTINGS, MATERIAL AND METHODS

2.1. Introduction

In this chapter are presented aspects that are general to all the next chapters (Study site, Image data sets, etc.), or additional information not provided in each of the chapter submitted for publications. This includes in particular general methodology information that are often not needed in publications formatted for specialized journals. I also provide here previews of some intermediate results (number of surveyed points, number of mapped polygons, etc.) to illustrate the relevant topics. These results are also provided in greater details in the following chapters.

2.2. Study site: Bunaken National Park and Bunaken Island

Bunaken National Park (BNP) is located at the northwest tip of Sulawesi, Indonesia (Figure 4). The location is at the core of the Coral Triangle, a vast area spanning Malaysia to Solomon Island, where the number of marine species is maximum (Hoeksema, 2007).

The BNP is one of the flagships of coral reef conservation in Indonesia. The park has been created in 1991 by decree of national government (Erdmann et al., 2004). The area includes part of the coastline around the nearby city of Manado, and five islands: Bunaken, Manado Tua, Siladen, Nain, and Mantehage (Figure 4). Since 1991 the Park is ruled by a zoning plan that has been designed using socio-economic constraints with the participation of numerous stakeholders for a better compliance.

Bunaken Island (BI) is located by 1.62379°N, 124.76114°E. It is surrounded by a simple fringing reef system, comprising reef flats, several small enclosed lagoons, and forereefs. At low tide, the reef flats are sometimes dry, and the maximum depth can reach above 2m at spring high tide conditions. Most of the time, depth would be between 40 and 1.50 meter. The tide regime is semi-diurnal, but with marked diurnal inequalities (Ray et al., 2005), with a maximum spring tidal range that can reach 2.52 m.

BI is famous for his wall dives that attract a high number of divers. Tourism is one the main activity in the park. The reef flats themselves are seldom visited by tourists, except one location dedicated to snorkelling activities. However, reef flats are systematically combed by the resident population at low tide to harvest crustaceans, molluscs and small fishes living in corals and seagrass beds. The gleaning activity occurs mostly on the south and east reef flats (personal observations). A survey of 7 fishermen suggested that destructive dynamite fishing is not occurring anymore around BI, since more than 20 years (personal data).

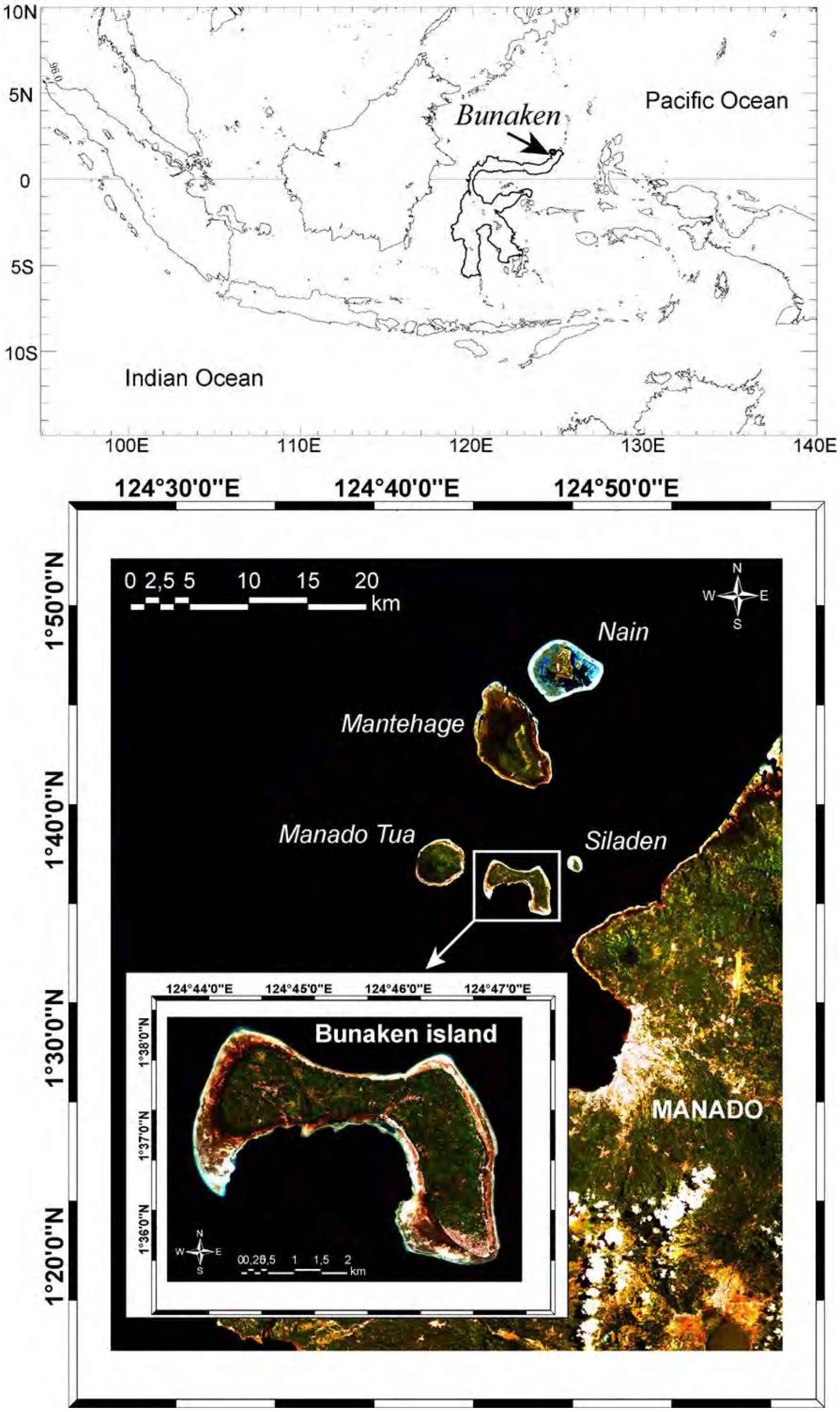

Figure 4: Location of Bunaken in Indonesia. Sulawesi is the island shaded in grey on the top panel.

NPI is one of the most studied Indonesian coral reef site (Table 5). From the various Bunaken NP study, particularly in Bunaken island (Table 4), Newman et al (2007), Le Drew et al. (2004) and Fuad (2010) were discussing issues related to remote sensing. Other studies are related to biodiversity, taxonomy, functional processes and effectiveness of the park management, especially in the early year of the park.

Table 5: Examples of Bunaken National park research activities in the past 20 years

Author	Year	Topic
Boyer et al.	1997	Bunaken (North Sulawesi, Indonesia) coral reef monitoring: a low-tech approach using volunteer scuba divers for data collection. Methods and preliminary results.
Boyer et al.	1999	Fish visual census and low-tech coral reef monitoring
Cerrano et al.	2000	Psammobiontic sponges from the Bunaken Marine Park (North Sulawesi, Indonesia): interactions with sediments
Schiaparelli et al.	2000	Ecology of Vermetidae (Mollusca: Caenogastropoda)
Bavestrello et al.	2001	Marine Biodiversity of Sulawesi Sea
Holden	2002	Characterisation of optical water quality
Puce et al.	2002	Zanclea Gegenbaur (Cnidaria: Hydrozoa) species from Bunaken Marine Park (Sulawesi Sea, Indonesia)
Erdmann and Boyer	2003	Lysiosquilloides mapia, a new species of stomatopod crustacean from Northern Sulawesi (Stomatopoda: Lysiosquillidae)
Turak & De Vantier	2003	Reef-building corals: Rapid ecological assessment of biodiversity and status
Fox et al.	2003	Recovery in rubble fields: long-term impacts of blast fishing
Erdmann et al.	2004	Building effective co-management systems for decentralized protected areas management
Le Drew et al.	2004	Spatial statistical operator applied to multidate satellite imagery for identification of coral reef stress.
Runtukahu et al.	2007	*Acropora* community composition at Siladen Island, North Sulawesi, Indonesia
Tazioli et al.	2007	Ecological Observations of Some Common Antipatharian Corals in the Marine Park of Bunaken (North Sulawesi, Indonesia)
Newman et al.	2007	Assessing the effect of management zonation on live coral cover using multi-date IKONOS satellite imagery
Fava et al.	2009	Possible effects of human impacts on epibenthic communities and coral rubble features in the marine Park of Bunaken (Indonesia)
Fuad	2010	Coral reef rugosity and coral biodiversity
Ricciardi et al.	2010	Assemblage and interaction structure of the anemonefish-anemone mutualism across the Manado region of Sulawesi, Indonesia
Tokeshi & Daud	2011	Assessing feeding electivity in *Acanthaster planci*

Bavestrello et al.	2012	Helicospiral growth in the whip black coral *Cirrhipathes sp*. (Antipatharia, Antipathidae)
Sidangoli et al.	2013	Institutional challenges to the effectiveness of management of Bunaken National Park
Setiawan et al.	2013	Community structure of reef fish in reef waters on Bunaken National Park, North Sulawesi
Patty et al.	2015	Community of reef fish on artificial reef Biorock in Siladen Island waters Manado city, North Sulawesi

Newman et al. (2007) used a pair of IKONOS images, between 2001 and 2004 to measure semi-quantitative changes in coral cover. The results were discussed by management zone, but no detailed maps of change are provided. They discuss that coral cover improvement (or not) could not be related to the various zones of the park, hence suggesting no clear effect of the park rules on coral growth or recovery. LeDrew et al. (2004) used a form of local indicator of spatial association (texture) to try to identify changes but the little reported variations are not discussed thematically. However, despite these early remote sensing studies, no habitat maps exist for BI or BNP till 2013.

2.3. Field work method for habitat typology

This thesis is built on field data, aimed at characterizing habitats (see definition in Introduction). Since we aim to describe habitats fully, we need to characterize cover, architecture and taxonomy which can be perceived only in the field. The description needs also to be representative and cover as much as possible of the different possible combination to capture the actual diversity of habitats (Andrefouët, 2008). Papers detailing field work are not many but see general survey techniques in English et al. (1997) and in a remote sensing context, see Roelfsema and Phinn (2010).

To inventory habitats, the work is guided by the imagery (Figure 5, step A). As many configurations in color and texture as possible are visited in the field, generally following long cross-reef transects where Global Positioning System (GPS) records and wide-angle photographs are taken systematically every minute, and/or when the bottom is visually changing (Figure 5, step B). GPS waypoints are preselected on the ENVI 4.7 software using the images that provide the latitude and longitude information with a precision generally better than 10 meter.

Back from the field (Figure 5, step C), the wide-angle photographs are visually analyzed on a laptop or desktop to give a semi-quantitative value of cover, rugosity, growth form, and dominant species. This is equivalent to the so-called Medium Scale Approach description (Clua et al., 2006) generally performed *in situ*, but which can be performed using photographs as well. Several photographs can be used for one habitat, and the average of the observations is kept. A spreadsheet is filled in Excel and a habitat ID-card can be created using PowerPoint (see examples in Appendix). The attributes of the habitat can be dependent on the context and for Bunaken, we considered the attributes listed in Table 5. Scopélitis et al. (2010) have shown the good agreement that is expected between a trained surveyor practicing MSA and the more quantitative approach based on cover measurements along a transect. The advantage of the technique applied here is its speed in the field. Typically 6 to 8 cross-reef transects sites can be covered in one day, depending on distances and transit time in a small *katinting* (small boat with a dedicated driver, stable and convenient for shallow and calm seas, Fig. 5), representing fifty to hundred waypoints, as an order of magnitude. For the forereefs, they were investigated using SCUBA in the 0-20 meter depth range using the facilities of the Bastianos diving resort located in Bunaken Island.

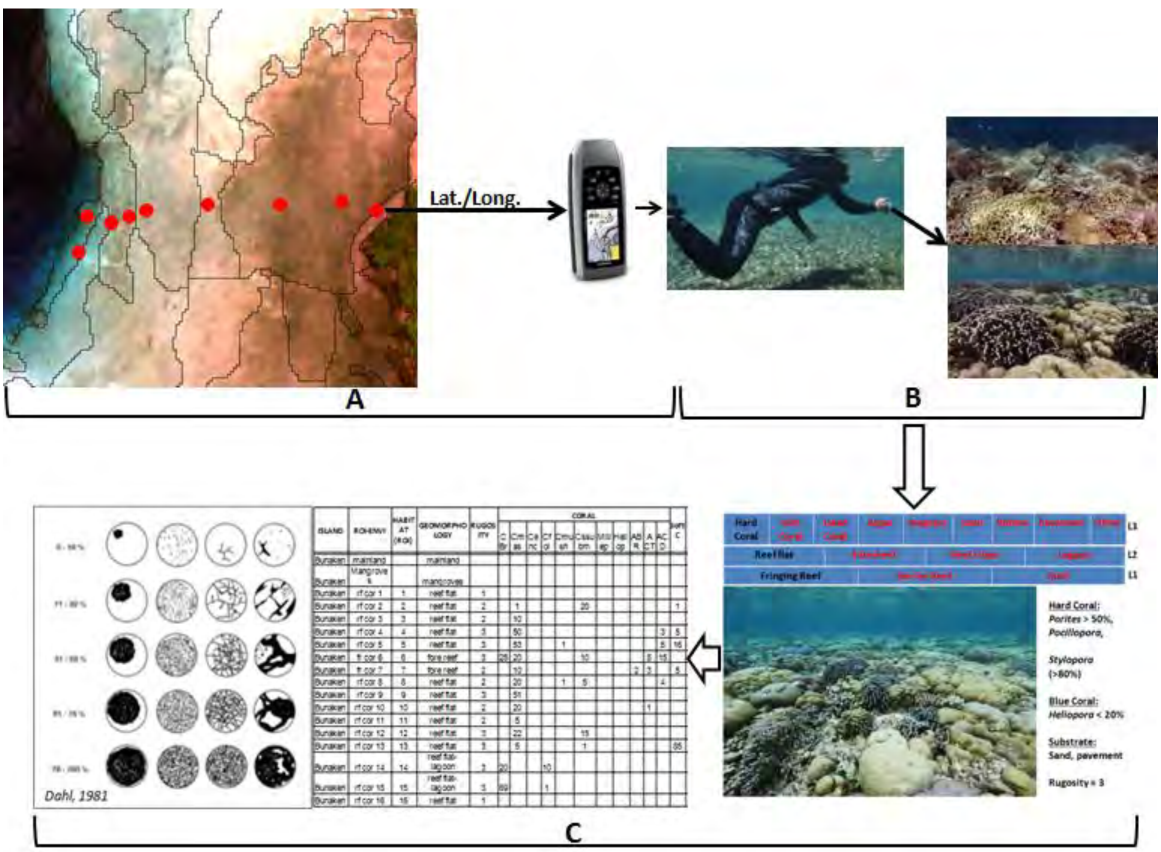

Figure 5: Flow chart for a field approach to characterize habitats in Bunaken island

Table 6: List of attributes for habitat description in Bunaken island. The percent cover of each variable is estimated using the MSA method.

Benthic Habitat	Remarks
CBr	Coral branching
Cmas	Coral massive
Cenc	Coral encrusting
Cfol	Coral foliose
Cmush	Coral mushroom
Cssub	Coral submassive
Millep	*Millepora*
Heliop	*Heliopora coerulea*
ABR	*Acropora* Branching
ACT	*Acropora* tabular
ACD	*Acropora* digitate
Soft C	Soft coral
DeadC	Dead coral
Sg	Seagrass
Alg	Algae
Turf	Turf algae
B.Cor	Black coral
Gorg	Gorgonian
Hyd	Hydroid
BS	Barel sponge
SE	Encrusting sponge
SB	Branching sponge
SO	Sponge (others)
RCK	Rock
RUB	Rubble
PAV	Pavement
S	Sand

The waypoints initially used for planning the survey are discarded and only the waypoints actually visited in the field are loaded in to ENVI 4.7 and Geographical Information System (GIS) software like QGIS Essen 2.14.3 or ArcMap 9.8. Attributes can be joined to each way point.

If the field work is well stratified, generally, there are no redundancy in the habitat descriptions: each waypoint is potentially a separate habitat. To verify this, the spreadsheet data can be analyzed by statistical clustering to detect similar habitats, and refine the typology. The process described here is thus different than previous studies in the early high spatial resolution studies (e.g., Capolsini et al., 2003), where habitats came necessarily from the statistical clustering of many field points, collected randomly or systematically, and not through a selection by image-guided stratification.

In Bunaken Island, we identified 175 habitats (see Chapter 4 and Appendix).

2.4. Training and accuracy assessment points

A first survey was conducted in May 2014 over the five islands. SCUBA gear or skin diving equipment, portable Global Positioning System (GPS) and underwater wide-angle camera were used during the survey. 830 stations (or waypoints) were investigated: 375 in Bunaken; 70 in Manado Tua; 84 in Siladen; 198 in Mantehage and 103 in Nain. However, in this manuscript we will focus hereafter only on Bunaken Island where the sampling has been the most intense.

A second survey was conducted in May-June 2015, using the same equipment, focussing on Bunaken, Manado Tua and Nain islands. The focus was accuracy assessment, thus collecting data on sites that have not been visited in 2014, also performing cross-reef photo transect. For the accuracy assessment and validation, we determined and verified the habitat classification of randomly selected stations, including255 points in Bunaken.

Finally, a third survey, in February 2016 was focussing on change detection and biodiversity (coral check-list with Dr Ofri Johan) only for Bunaken Island, but it brought new validation data for accuracy assessment with 152 additional points.

The Figure 6 summarises the ground-truthing effort achieved for Bunaken Island for training and accuracy assessment for habitat mapping.

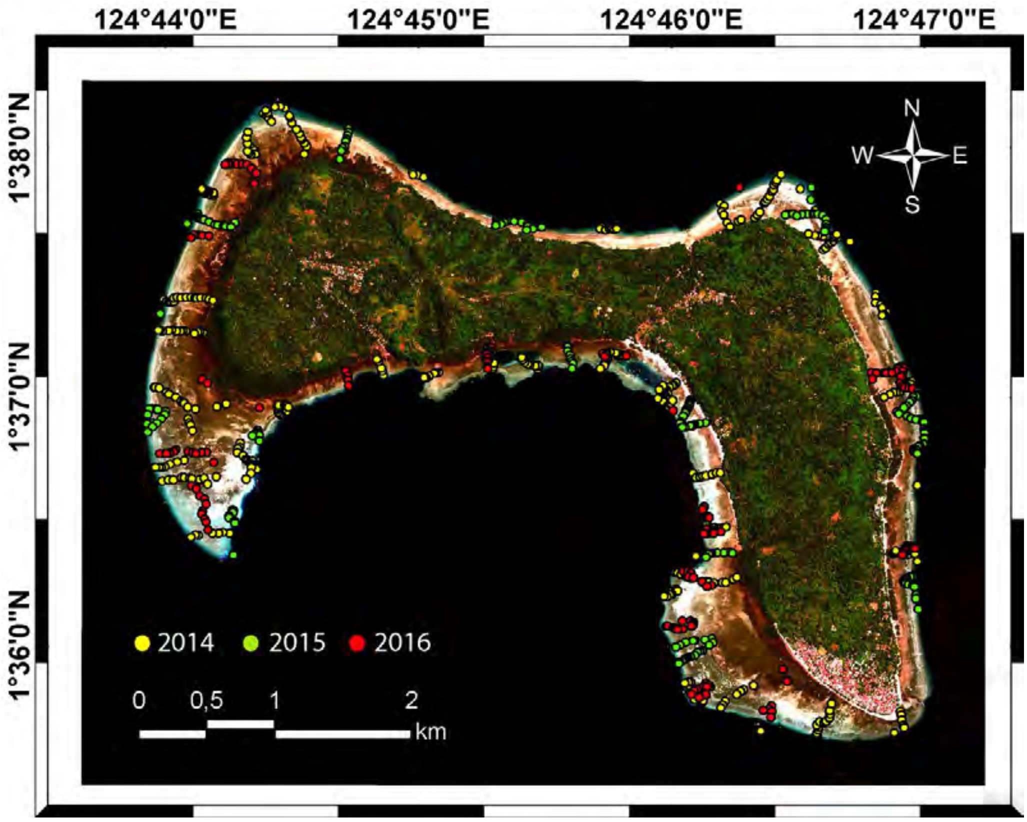

Figure 6: Summarises ground-truthing achieved 2014, 2015 & 2016. In addition, forereefs were investigated by SCUBA almost for the entire periphery of the island.

2.5. Photo-interpretation, digitization, thematic simplification, and final typology of mapped habitats

The habitat map is created in several steps, and entirely by photo-interpretation. First, polygons of habitats are digitized using the ENVI 4.7 software, and its "Region of Interest" toolbox. Polygons are defined by identifying their boundaries based on homogeneous color and texture on a true color RGB composite, and using the same image enhancement all the time for consistency. Enhancement is changed only when mapping deeper areas where it is necessary to stretch the green and blue bands.

This process was achieved using the Geoeye image acquired the 28 March 2014, as it was the most recent image available at the time of the mapping. The image is of excellent quality and very clear for photo-interpretation. 401 polygons are created for Bunaken Island, including a mangrove and land polygon. Villages, houses, roads and also jetties are included in this "land" polygon (Fig. 7).

Second, for the polygons which overlap the training transects, polygons are assigned to one of the identified habitat. Then, if there are polygons that are similar in color and texture but have different habitat labels, we need to redefine a common habitat, generally by losing thematic precision. For instance, one polygon can be initially labelled as "Dense seagrass beds with *Thalassia* and *Enhalus* dominant species" and another as "Dense seagrass beds with *Thalassia* and patchy branching *Porites* coral" based on ground-truthing and the initial habitat typology. If they look exactly the same visually and statically (by looking at the mean and standard deviation of the bands for each polygon, Figure 7), the polygons are both assigned to a less precise "Dense seagrass beds with *Thalassia*, and possible occurrences of *Enhalus* and branching *Porites* coral". It means that there is flexibility (and uncertainty) in what the habitat in these polygons can be made of. A convenient tool in ENVI 4.7 to decide if polygons have to be thematically and physically merged is the n-D Visualizer tool, an interactive 3D visualisation of the pixels of each polygon in the radiometric RGB space (Figure 7). Other statistics can be also provided, but the 3D visualization is very useful to take decision on the fly.

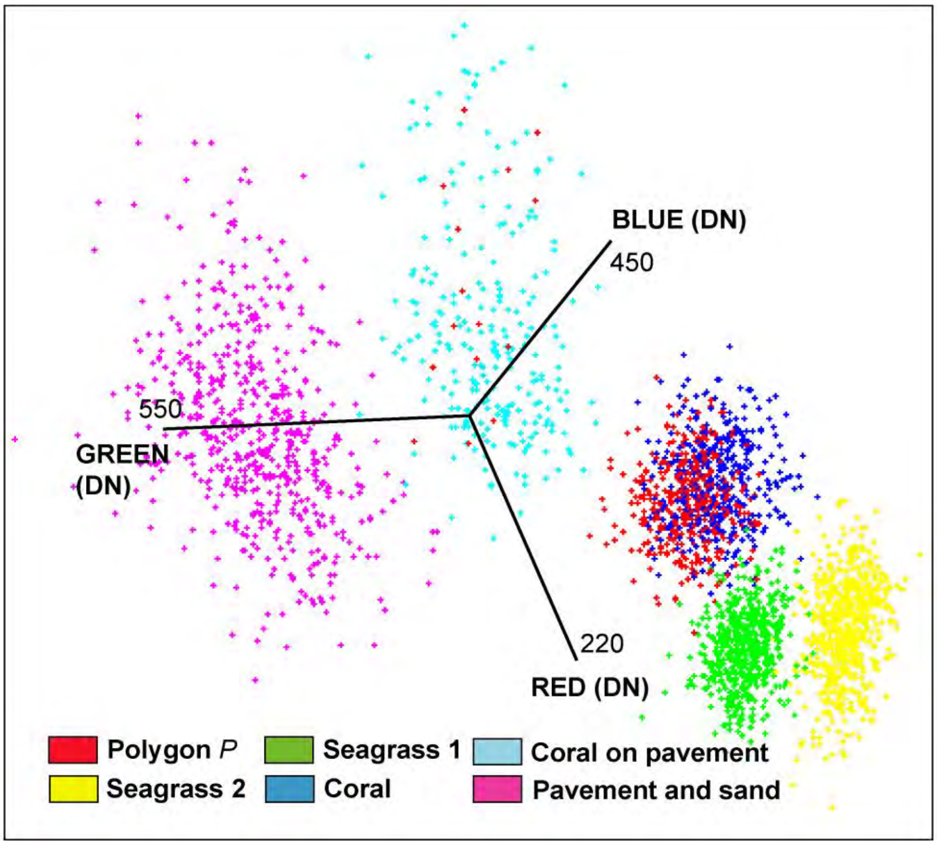

Figure 7: Example of visualisation from the interactive ENVI 4.7 n-D Visualizer tool, to decide habitat class assignment for a polygon *P* with the red pixels, all other classes being known. The red pixels overlap the blue one, hence it will be assigned the same name (here, "coral"). DN is the radiometric unit used here (DN: digital count)

Other polygons that do not overlap with training ground-truthing points are assigned to one habitat based on the similarity with the aforementioned training polygons, and also by using the n-D Visualizer tool as an objective guide based on spectral information. However, other information than spectral are used to take a decision, such as position within the reef, and type of nearby polygon. Hence, photo-interpretation is used, and not only an automatic classification based only on spectral properties.

The process above is done geomorphological zone by geomorphological zone, for instance processing together all seagrass habitats on the shallow terraces, then the covered hard bottom of reef flats, then the crest, then the forereefs.

A final product is thus composed of 1) the habitat map in a raster ENVI format, and 2) the typology of mapped habitats which is a simplification of all the habitats that have been seen in the field. The raster image can be exported into a GIS software format and vectorised, and the product is finished by joining to each polygon the final habitat table attributes. Surface areas of all polygons are generally computed and added to the attribute table.

We point out that because the main areas are shallow reef flats with about 1 meter depth, no depth correction was applied. The forereefs are also entirely photo-interpreted.

2.6. Accuracy assessment for habitat mapping

The accuracy of the map is quantified using a confusion matrix. It reports for the control points the number of control pixels in each habitat class that have been correctly classified, and indicate in which classes the misclassified pixels have been assigned (Table 7). For this, the control points need to be described using the same simplified habitat typology retained for the habitat maps.

Table 7: Example of confusion matrix (or error matrix) with 4 categories

	Pixel Reference data					
Classification data	**Coral**	**Algae**	**Seagrass**	**Sand**	**Row Total**	**User accuracy**
Coral	90	5	10	20	125	90/125
Algae	20	45	25	7	97	45/97
Seagrass	16	15	100	32	163	100/163
Sand	9	0	27	55	91	55/91
Column Total	135	65	162	114		
Producer accuracy	90/135	45/65	100/162	55/114		

From the confusion matrix, a number of metrics can be computed and we will use here the overall accuracy (OA), the user accuracy (UA) and the producer accuracy (PA) computed using the ENVI 4.7 software. These are the most common metrics used (Foody, 2002). Other metrics (e.g., Kappa index) compare the accuracy of the classification with the accuracy of a classification that would have been produced randomly. The metrics is a statistical test that evaluates how far the classification is from a random classification. Considering the method we use (photo-interpretation), the Kappa coefficient is not really relevant.

The definitions are provided hereafter:

Overall accuracy (OA): the percentage of control pixels correctly classified, with 100% accuracy being a classification where all reference site were classified correctly. This value is for the entire classification.

User's Accuracy (UA): this is an accuracy metric provided for each individual class. The User's Accuracy is calculated by taking the total number of control pixels correctly classified for a particular class and dividing it by the total number of pixels classified in that class.

Producer Accuracy (PA): this is also an accuracy metric provided for each individual class. The Producer's Accuracy is calculated by taking the total number of control pixels correctly classified for a particular class and dividing it by the total number of control pixels in that class.

2.7. Multi-sensor image data sets for change detection analysis

One of the main assets of this research project is the unique time-series of VHR images acquired by the INDESO project for Bunaken Island. It is composed of 21 images that cover entirely or partly Bunaken Island. The time-series includes 4 types of images whose characteristics for the project are presented in Table 8 and 9:

Table 8: Main characteristics of the type of images used in this study.

Satellite	Launch date	Spatial resolution	Spectral resolution
IKONOS 2	24/09/1999	4 m	4 bands : B, G, R, NIR
Quickbird 2	18/10/2001	2.4 m	4 bands : B, G, R, NIR
Geoeye 1	06/10/2008	2 m	4 bands : B, G, R, NIR
Worldview 2	08/10/2009	2 m	4 bands : B, G, R, NIR

Note that Worldview-2 is a 8-band sensor, but only 4 were available for the INDESO projects, which is adequate as the goal was to compare changes using other 4-band multispectral sensors. All good quality images available in the various sensor archives were acquired for the project. In addition, in 2013, new Geoeye images were specifically tasked for acquisition in March-May 2014 and 2015 (Table 9).

Table 9: Characteristics of images used for this study. Glint refers to sun reflection at the sea surface. Except for image 27/11/2009, environmental conditions were good (see Comments) to very good (no Comments).

Sensor	Acquisition Date	Spatial resolution	Comments	Coverage
IKONOS 2	29/06/2001	4 m	some clouds	East
IKONOS 2	07/07/2001	4 m		West ¾
IKONOS 2	10/07/2001	4 m		West ¾
IKONOS 2	16/11/2002	4 m	minor glint	South ½
IKONOS 2	03/03/2003	4 m		South east
IKONOS 2	01/08/2003	4 m		South east
IKONOS 2	03/10/2003	4 m	haze	South east
IKONOS 2	06/06/2004	4 m		Complete
Geoeye-1	27/11/2009	2 m	wind, wave and haze	Complete
Worldview	09/03/2010	2 m		Complete
Quickbird	10/05/2011	2.4 m		Complete
Geoeye-1	08/12/2011	2m	glint, haze	South
Quickbird	10/04/2012	2.4 m		East
Quickbird	14/05/2012	2.4 m	minor glint	Complete
IKONOS 2	23/10/2012	4 m	minor glint	Complete
Quickbird	12/11/2012	2.4 m		Complete
Quickbird	24/05/2013	2.4 m		Complete
Quickbird	24/05/2013	2.4 m		Complete
Geoeye-1	28/03/2014	2 m		Complete
Quickbird	10/02/2015	2.4 m		East
Quickbird	15/03/2015	2.4 m		West ¾

CHAPTER 3. REVISITING BUNAKEN NATIONAL PARK (INDONESIA): A HABITAT STAND POINT USING VERY HIGH SPATIAL RESOLUTION REMOTELY SENSED

3.1. Introduction

Coral reef habitat mapping using multispectral (3 to 8 bands) very high spatial resolution (1-4 meter) remote sensing images is now a fairly well understood field. The scientific literature provides numerous examples that have clarified the potential of using images, with or without ground-truthing. May be more interestingly, many scientific, management and conservation programs use habitat maps derived from remote sensing as part of their toolkits. Large areas, sometimes entire country coastlines, have also now been mapped at very high spatial resolution (VHR) (Maina et al., 2015). Less than ten years ago, the situation was quite different, and we can state that progresses have definitely been made for the benefits of users, either scientists or managers, interested in spatial products. However, the thematic resolution remains limited to, at most, few tens of habitats. This limit has been pushed by using photo-interpretation technique, instead of automatic classification and segmentation algorithms (Andréfouët, 2008).

Indonesia has vast coral reef areas, estimated at 50.000 km^2 (Done, 2011), which are renowned for their biological diversity and ecological complexity, and are located at the global centre of tropical marine biodiversity. Within this broad area, reef-building coral diversity exceeds 500 species which correspond to more than 70% of the total Indo-Pacific species (Veron, 2000).The Indo-Pacific area supports the highest diversity of reef-associated fishes (Allen and Steene, 1994), and is clearly of global significance as the key reservoir of tropical marine biodiversity (Turak and DeVantier, 2003). However, while numbers exist for various taxa, it would be problematic to state how many reef habitats can be found in Indonesia, or for a given archipelago, or even for a given reef. We use here the definition of habitat presented in Chapter 3. Obviously, it is possible to list a number of generic coarsely-defined habitats (rubble, sand, various coral and seagrass habitat), but the number of combination of geomorphology-architecture-cover-dominant species is not known.

We suggest that remote sensing, especially using VHR images, could be used to guide a first detailed inventory of all habitats found an Indonesian reef. In doing so, we aim to also assess how far habitat maps can represent the diversity of habitats found on situ. Do photo-interpretation products have reach their thematic resolution limits, or is it possible to do better and enhance the thematic resolution of the maps?

To investigate the limit that can be reached by photo-interpretation to map Indonesian reefs; we use Bunaken Island as case study to test a new approach, and a Geoeye-1 multispectral image at 2 meter resolution. We discuss our findings in terms of contribution to the knowledge of Indonesian biodiversity, and also in terms of potential uses, or not, of the newly created map.

3.2. Material and Methods

3.2.1. VHR Image

We used the Geoeye-1 image acquired 28 March 2014 for the habitat mapping. The 2-m resolution image was of excellent quality. Since we used photo-interpretation, the raw image was used without pre-processing.

3.2.2. Habitat typology

The first step was to identify as exhaustively as possible the habitats of Bunaken Island (BI), to infer a habitat typology. For this, field work is conducted using visual census technique at medium scale level of perception (Bianchi et al., 2004; Clua et al., 2006) and by conducting large-scale (i.e. crossing the entire reef from mangroves to fore reef) transects (Andréfouët, 2008). In other words, we describe semi-quantitatively benthic cover (Dahl, 1981), rugosity, and dominant communities that differ visually along the reefs while crossing its different geomorphological zones (see Tables on the Appendix). The six geomorphological zones are Crest, Lagoon, Reef Flat, Terrace, Slope, and Wall.

Before the surveys, the location of each training transect was selected using the 2014 GEOEYE satellite images and the ENVI+IDL program v4.7. The transects are selected by photo-interpretation to capture a maximum of configuration according to the image color and texture. The number of transects is a trade-offs between time available and areas that are potentially interesting to visit to cover all configurations. More details on fieldwork are provided in the Chapter 2 of this thesis, including the level of sampling effort for training and accuracy assessment.

A key aspect of this work is that habitats seen in the field are iteratively added to the typology if they appear, visually, different than the previously included habitats. This is in contrast with traditional techniques that infer a habitat typology generally after a statistical hierarchical clustering performed on the overall set of benthic data. But this method implicitly aims for a simplification of the observations, with habitats defined based on the statistical clusters. Here, we postulate that habitats that are visually different need to be included in the typology, exhaustively. This is in agreement with our objectives of describing as exhaustively as possible the biodiversity of habitats for Bunaken.

The typology is thus not a statistical result. However, after the typology is compiled and each habitat is described, we applied a metric Multi-Dimensionnal Scaling (mMDS) ordination (Kenkel and Orloci, 1986) to the benthic data. Benthic cover data were analyzed with the Primer7 software. We did not include Rugosity (a semi- quantitative descriptor, in the analysis in order to only use data of the same types (i.e., percentage data). The mMDS is suitable to project the habitats in a multi-dimensional space while minimizing the distance between habitats as best as possible. Generally, mMDS is used to identify clusters as well. Here, with this technique, we actually aim to check how habitats in the typology are redundant which is not the typical use of mMDS. Obviously, habitats very close in mMDS plots could be considered as duplicates, and in this case duplicates need to be removed, but only if visual differences were not due to Rugosity. If the mMDS produces a cloud of points (habitats) without clear groups of habitats, then the visual identification, and MSA description, has met its objectives. Finally, it must be pointed out that the stress factor produced by mMDS can be low in our analysis. A low stress factor means that the discrimination on the mMDS 2D ordination plot (or 3D-plot) is not effective with clusters that are actually not real clusters. But if we found that habitats are already spread out in a non-optimal ordinal representation, this confirms anyway that habitats are not duplicates.

3.2.3. Habitat mapping for a very high thematic resolution of habitats

We had to devise a 2-steps approach to create a map that contains as much habitat information as possible. The main limitation is obviously that even at very high spatial resolution, a multispectral image cannot discriminate all possible habitats based on spectral or textural information, because many habitats would be similar on the image. There are compromises to be made. Most previous studies have made this compromise by simplifying the habitat typology (see Chapter 2), which we do not want to do.

Here, we first segment by photo-interpretation the image to create polygons of what should be homogeneous habitats. This product would represent the finest possible VHR product if each polygon could be labelled with a habitat, or a set of habitats without errors. Ideally for the sake of convenience, each polygon would include only one habitat found in the typology. Two different polygons can be of the same habitat of course. Then, using the habitat typology and field data, we labelled each polygon, but practically, in doing so, it was necessary to link much more than one habitat to each polygon. Indeed, training field data shows clearly most of the time the presence of several habitats by individual polygons.

The second step is generalization to polygons without training data. For this, spectral similarity between polygons are analyzed using the Jeffries-Matusita transformed divergence distance, provided in the ROI tool of the ENVI software (typically to test end-member separability). The tool ranked polygons of known habitats by their spectral similarity (using here only the RGB bands) *versus* the “unknown habitat” polygon to characterize. However, many polygons that are radiometrically close were deemed not suitable for generalization due to their positions. In other words, the spatial arrangement (distance) between polygons was a factor that we also took into account. Polygons without known habitats were merged with the closest polygon, based on spectral criteria first and then spatially. The result is a second map, with the same complexity of habitats, but with less polygons.

3.2.4. Accuracy assessment for a very high thematic resolution of habitats

The results from the previous steps are a suite of polygons, for which a list of habitats, from the typology, is provided. A key aspect is that the spatial position of one habitat of the list within the polygon is not known considering how a list of habitats is assigned to a given polygon. We just know that the habitat is in the polygon, or that it should be there.

Thus, accuracy assessment of the habitat map in this context would be different than a classical error matrix (see Chapter 2). Indeed, here, we have a multiple choice solution for each polygon. A solution to evaluate the accuracy is thus, also using ground-truth data, to create a error matrix per polygon where control data are available. However, this assessment would be based only on the correct presence/absence of each habitat in each polygon. From the individual polygon evaluation, an overall accuracy of the map can be derived by averaging the scores across the polygons.

3.4. Results

3.4.1. Habitat typology

The habitat typology and the characteristics of each habitat are provided in Appendices 1 and 2. The Appendix 2 provides ID-card for each habitat, with a simplified presentation of the habitat attributes, and a representative picture. However, this picture is only one among many that represent the habitat, and a user should not just limit his view of the habitat based on this picture, but based on the full range of percentage cover.

We found 175 different habitats around Bunaken Island. This is a remarkable value for 5 km^2 of reefs. Richest geomorphological zones were the reef flats (98 habitats), followed by terraces (40), crests (31) slopes (28), walls (9) and lagoons (6).

The nMDS conducted for each geormorphological zones are presented in Figure 8. Overall, the results confirm that there is little redundancy between habitats, with clouds of spread habitats and not presenting suspicious groupings that would reveal similar habitats. Some groups can be seen, for instance in the Reef Flat results. These groups naturally reflect the dominance by corals, or rubble for instance, but there are very few overlaps between pair of habitats. Several of them (ex: 43 and 83, Reef Flats) are actually quite different habitats, pointing out that their proximity is just due to the 2D perspective on their real distance and position.

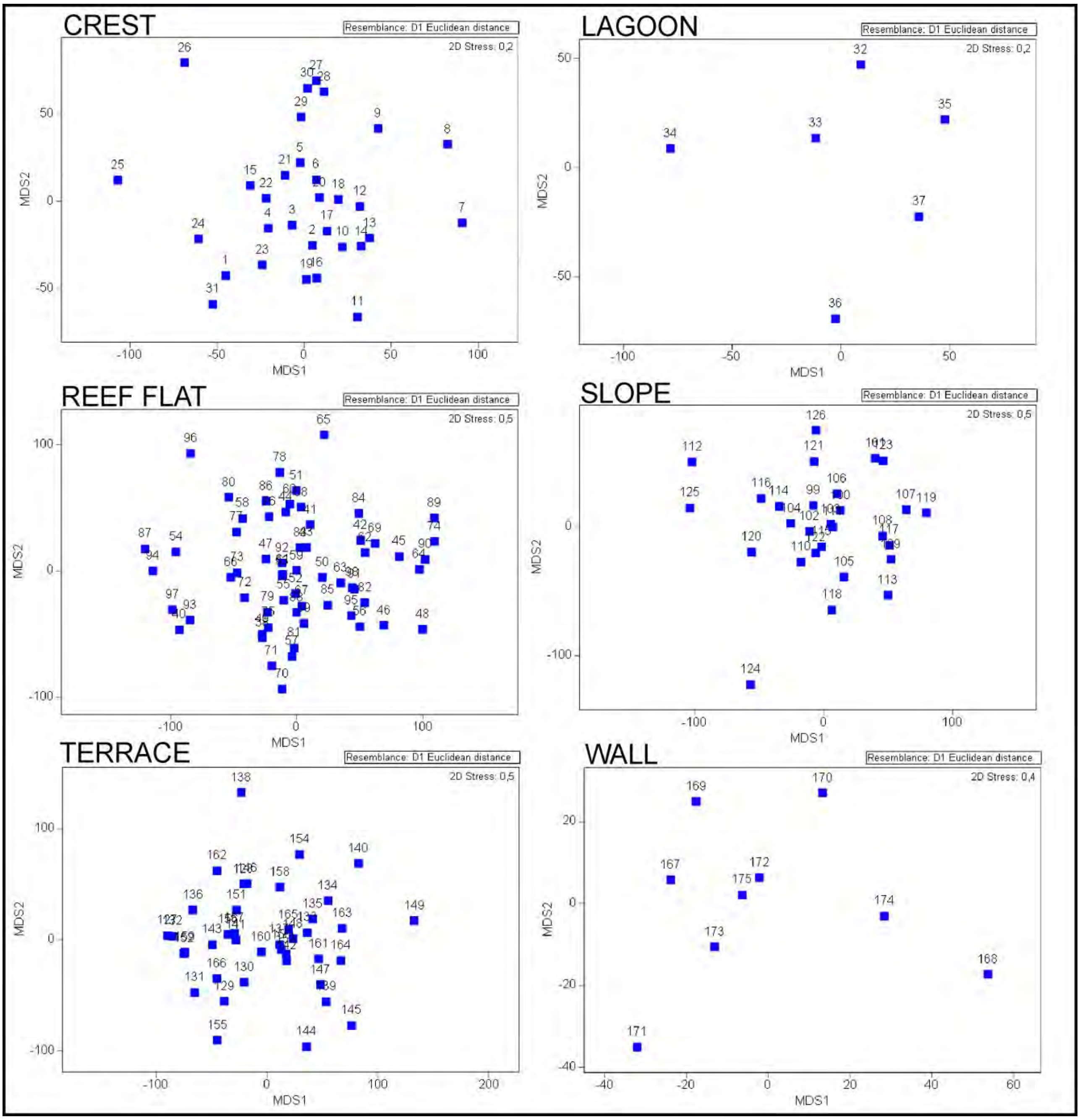

Figure 8: nMDS plots for each geomorphological zone. The plot illustrates how well the habitats can be spread out based on a distance matrix between habitats (euclidian distance on percentage values).

3.4.2. Habitat mapping

The first segmentation pass, by photo-interpretation, yielded a total of 401 polygons (plus mangroves and land). An example illustrating the level of detail is provided Figure 9. For the walls, for which virtually no information can be provided by the image, the limit of the polygon was set at each change of direction of the edge of the reef.

The polygons intersecting ground-truth training cross-reef transects (training polygons) were then linked with the habitats found on the transects, using the habitat ID in the typology. The second pass, to assign a habitat list to habitats that did not cross training transects, could work for about less than 50% of the remaining polygons. The other 50% left were polygons judged spectrally too different to simply receive directly the same list of habitats as the training polygons. In this case, we assigned directly the habitats. Overall, the final segmentation, with different combination of habitat lists per polygon, is a 194-polygon segmentation. The lower number of polygons is due to the merging of polygons that have the same list of habitats. The Appendix 3 provides the list of habitats per final polygon.

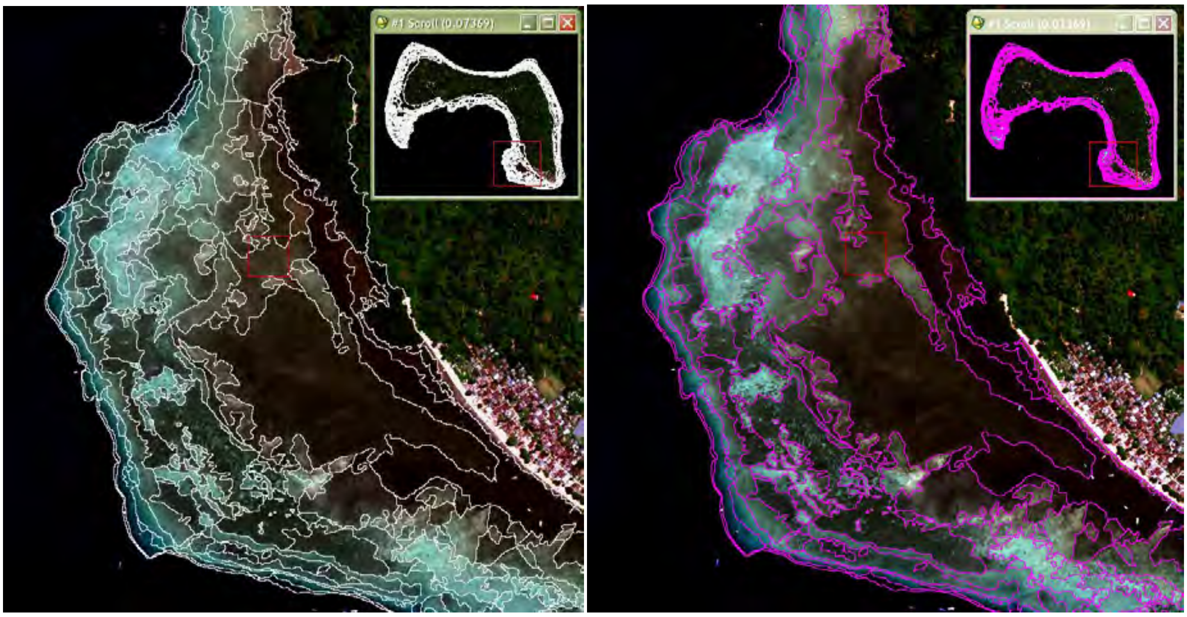

Figure 9: Illustration of polygons created by photo-interpretation of the Geoeye-1 image. Only the boundaries are visible, to show the homogeneity in color and texture in each polygon. On the left side, the original segmentation. On the right side, the simplified one.

3.4.3. Accuracy assessment

The 2015 data collected for accuracy assessment along cross-reef transects were used to quantify producer and user accuracy for polygons that crossed these transects. These transects were snorkelling transects from crest to shore. We evaluated thus the accuracy for crest, reef flats and terrace geomorphological zones. Also, the exercise would be meaningless for other zones (walls, slopes, and lagoons) that have been exhaustively covered for training by SCUBA (i.e., almost all polygons of these zones were covered during the training phase as these classes are less extensive).

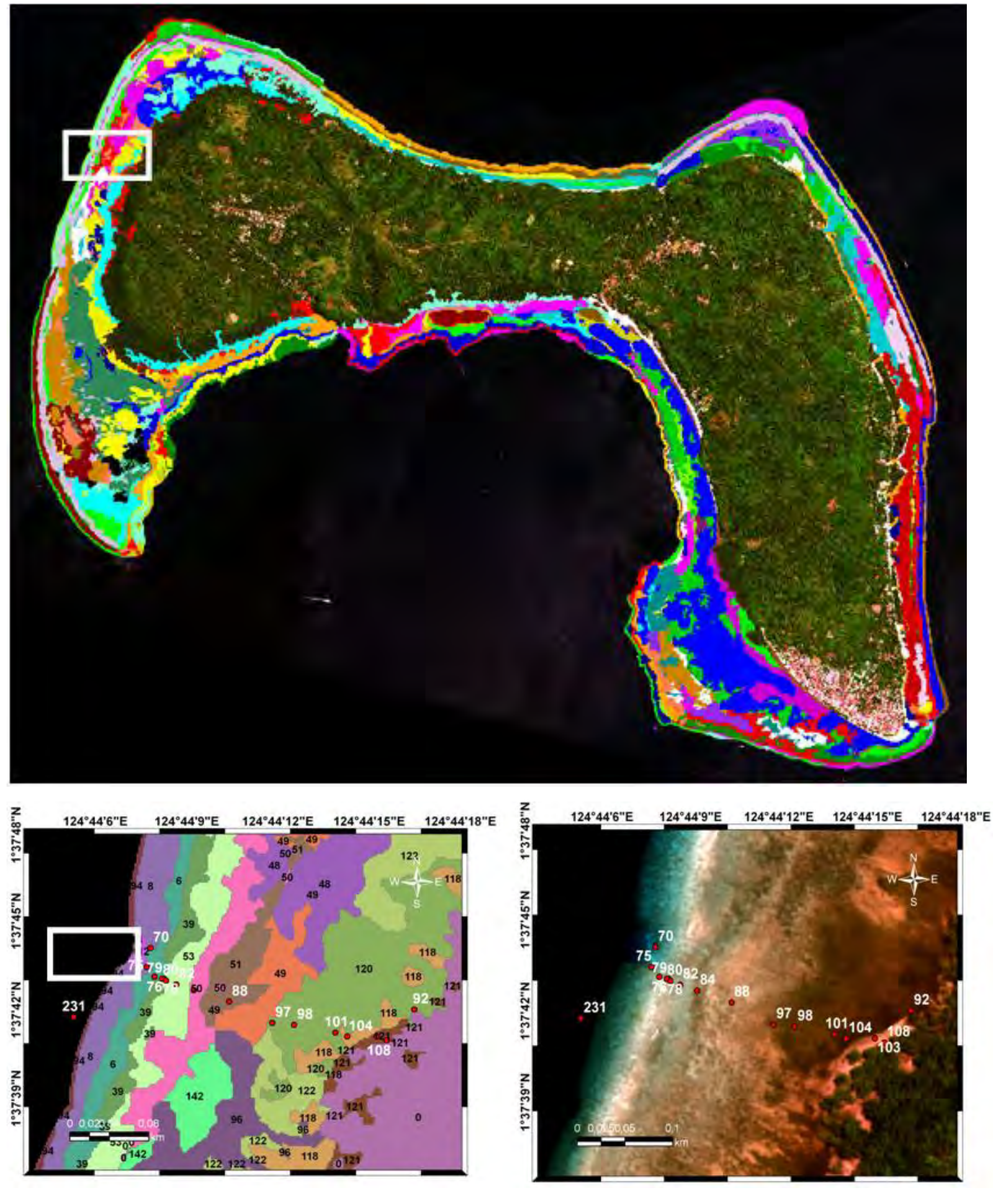

Figure 10: On top, visualization of the mapped polygons, and below, detail for an accuracy assessment transects on the east side of the island. Numbers in white are GPS records of position (with in situ pictures between them), and numbers in black are polygon numbers (See Appendix 3).

The transect in Figure 10 crosses polygons 112, 6, 8, 49, 50, 51, 53, 118, 120 and 121. The composition of these polygons based on ground-truthing is provided in Appendix 4, to be compared with the mapped composition of the same polygons in Appendix 3 (and 4).

We point out that even if we use the same words, the user and producer accuracy (related to commission and omission errors) that we had defined in Chapter 1 are in fact quite different than here. Here, we quantify omission and commission errors based on habitat presence/absence per polygon, and not based on individual pixel assignment to classes. The main issue we observe, and which is valid for all other transects, is substantial commission errors (commission error = 100% - User accuracy, see Foody, 2002). In other words, the mapping assigns more habitats to a polygon than actually present. There are no virtually no omission errors (and none on the example provided in Appendix 4). In other words, all habitats actually present based on the ground-truthing are part of the list. The level of commission errors is dependent on the size of the polygon, and the specificity of the habitat(s) inside the polygon. Commission errors are easily explained by the process of habitat assignment to each polygon, since each habitat found on radiometrically similar polygons around the island can be assigned to the focal polygon. High-level of commission errors is not truly satisfying for users, even if the actually present habitat is listed.

3.5. Discussion and conclusion

The method we applied to describe the habitats of Bunaken with the objective of representing the highest possible thematic complexity has benefits and drawbacks. We discuss both hereafter.

The first benefit of the method we applied is that a rich typology of habitats is highlighted, without simplification of the range of configurations found in the field. With 175 habitats, this is the highest score for a fringing reef since applying this methodology (Andrefouët, pers. comm.). It is also possible that there are more habitats, since we did not go everywhere. We also found that the richest areas were the reef flats, terraces, and crests, before the forereefs (slopes and walls). These later areas are biologically diverse, but not in term of habitats. Also, it must be emphasized that the level of sampling effort for such a small reef was fairly intense. However, other sites in the Indo-Pacific area, also well visited, seldom yielded as many habitats, or for much larger area. As a comparison, it was found 140 habitats on the island of Mayotte (in the Mozambique Channel) during a 2-weeks survey that took place in May 2016, on lagoon, fringing, patch and barrier reefs. We suggest that Indonesian reefs will set a new standard in terms of habitat richness per km^2 of reef. This is another crown for Indonesian marine biodiversity.

The map itself highlights complex spatial patterns. The 194 final polygons offer a fine representation of the patchiness of the habitats. Each polygon has a specific series of habitats that can be found in the domain of the polygon, but where exactly remain unknown. It is only the small size of the polygons which make the mapping quite precise to locate precisely the habitats. However, the handling of the information is not easy, and probably it will be overwhelming for most users. Specifically, taking decisions based on an accuracy matrix specific for each polygon will probably be too problematic. Therefore, shifting habits to use a very high thematic resolution map for a variety of application may be difficult. For instance, habitat maps are routinely used these days for systematic conservation planning, under the criteria to include for instance 10% of the area of each habitat in a network of marine protected areas (e.g., Hamel et al., 2013). Applying these criteria with these kinds of maps will be impractical. In fact, the value of the map and its information is primarily really when studying habitats, and comparing reefs, not necessarily to study other aspects combined with some habitat information.

In this chapter, we created a unique remote sensing product that makes justice to the richness of Bunaken Island and its habitats. It is based on a substantial field effort, on simple remote sensing techniques, and required handling large numbers of entities, with lots of manual processing. These expert-based procedures are difficult to reproduce exactly the same way from one producer to another. This is often seen as a major problem - and it is a problem - but it is also the main compromise to accept if the goal is to represent at its true level the habitat biodiversity.

CHAPTER 4. CORAL MORTALITY INDUCED BY THE 2015-2016 El-Niño IN INDONESIA: THE EFFECT OF RAPID SEA LEVEL FALL

4.1. Introduction

El Niño-Southern Oscillation (ENSO) is the most important coupled ocean-atmosphere phenomenon impacting climate variability at global and inter annual time scales (McPhaden, 2007). The consequences on coral reefs have been well documented, especially since the 1997-1998 massive coral bleaching event, which reached planetary dimension (Hoegh-Guldberg, 1999). El Niño increases temperature in several coral reef regions and induces zooxanthellae expulsion from the coral polyp, resulting in coral colony looking white, hence "bleaching". If the situation persists the coral colony eventually dies. Coral bleaching intensity has been related to different temperature thresholds, other environmental factors and stressors, and type of zooxanthellae and corals (Baker et al., 2008). Bleaching episodes due to ocean warming were recorded during the strong 1982-83 El Niño in Australia (Glynn, 2000) and have since been reported worldwide in several instances (Guest et al., 2012; Wouthuyzen et al., 2015). The last bleaching episode has occurred in 2015-2016 during what occurs to be the strongest El Niño event on record (Schiermeier, 2015). Bleaching events were often global in the past, including Indonesia (Suharsono, 1990; Guest et al., 2012; Wouthuyzen et al., 2015). Last reports for Indonesia in 2016 are still under analysis, and survey locations are presented at http://reefcheck.or.id/bleaching-indonesia-peringatan/ ("Reef Check Indonesia," n.d.). It is thus assumed that coral bleaching induced by ocean warming will be the main culprit if monitoring surveys report post-El Niño coral mortalities.

While in Bunaken National Park in February 23rd – March 5th 2016 for a biodiversity survey, we noticed recent mortalities on the upper part of many massive colonies on several reef flats. This prompted a systematic investigation of the phenomenon spatial distribution. We report here observations on what appears to be the first significant impact of the 2015-2016 El Niño on Indonesia reefs. Unlike what is expected during such a strong event, the mortality was not related to warm water induced-bleaching, but could be tracked to rapid sea level variations. Coral mortality data around Bunaken Island are provided, and we investigate various altimetry and sea level anomaly data sets to explain mortality. The clear link between mortality and sea level fall calls for a refinement of the hierarchy of El Niño impacts and their sequences on coral reefs.

4.2. Material and Methods

Bunaken National Park (BNP) is located at the northwest tip of Sulawesi, Indonesia. The location is at the core of the epicenter of marine biodiversity, the so-called Coral Triangle, a vast area spanning Malaysia to Solomon Island, where the number of marine species is maximum (Hoeksema, 2007). BNP includes several islands with Bunaken Island (1.62379°N, 124.76114°E) one of the most studied Indonesian reef site. Bunaken is surrounded by a simple fringing reef system, comprising reef flats, several small enclosed lagoons and forereefs. The tide regime is semi-diurnal, but with marked diurnal inequalities (Ray et al., 2005), with a maximum spring tidal range that can reach 2.52 m.

Two previous BNP surveys for habitat mapping, in May-June 2014 and May-June 2015, did not show any significant signs of widespread mortalities on reef flats. Different species of corals were frequently exposed above water level at low spring tide, yet they were entirely alive (Fig. 11). Microatolls were present. They have not been studied in Bunaken NP, but by similarity with other sites, their growth is likely constrained by a Mean Low Water (MLW), between Mean Low Water Neaps (MLWN) and Mean Low Water Springs (MLWS) (Smithers and Woodroffre, 2000; Goodwin and Harvey, 2008). Several reef flats were characterized by compact communities of massive and semi-massive colonies that could be described as keep-up communities limited in their vertical growth by the MLW (by analogy with the terminology of Holocene reefs provided by Neumann and Macintyre, 1985). In contrast with the 2015 observations, in late February 2016, during a coral biodiversity census survey, we noticed the widespread occurrences of dead massive corals and we performed a systematic investigation on the spatial distribution of the phenomenon. All reef flats around Bunaken Island were visually surveyed and recent mortality was recorded (presence/absence). Geographic coordinates of the presence of mortality were compiled to map its extent. Then, in different locations around the island, mortality was measured on six reef flat locations characterized by high coral cover and different dominant massive coral species, principally *Porites lutea* and the octocoral *Heliopora coerulea*, using six 10-meter long Line Intercept Transect (LIT) (English et al., 1997). We recorded the percent cover of live and dead tissue for each coral, the species/genus for each coral, and substrate categories between colonies.

A clear sharp horizontal limit of tissue mortality was present in impacted colonies. The distribution of dead tissue between colonies and among colonies (Fig. 1) suggested that mortality was related to sea level variations, with increased aerial exposure time during the last few months. In order to test this hypothesis, different sea level anomaly products were investigated, based on their temporal coverage and spatial resolution. First, we used gridded altimetry data in terms of Absolute Dynamic Topography (ADT), from the Archiving, Validation and Interpretation of Satellite Oceanographic Data center (AVISO) at the spatial resolution of ¼° and daily temporal resolution. ADT provides the sea level with respect to the geoid. Data is available from 1993 to 2016, allowing a long-term comparison of the sea level trends. The mean ADT over the period were extracted for a small box next to Bunaken Island (1.5-1.7° N; 124.5-124.8° E), a larger box (3 by 3 degrees around the smaller box) centered on Bunaken Island and including the north of Sulawesi and Tomini Bay in the south, and for the entire Indonesia (-14.9-10.0°S, 94.9-140.0°E). The difference between the minimum value (observed in September 2015) and the 2005-2014 mean or the 1993-2016 mean periods were also computed.

Second, to extract geophysical information from higher spatial resolution altimeter data, we used the along-track measurements from SARAL/AltiKa Geophysical Data Records (GDRs) distributed by the AVISO service (http://www.aviso.altimetry.fr/fr/). This data set was chosen because the new Ka-band instrument from SARAL has a finer spatial resolution and enables a better observation of coastal zones (Verron et al., 2015). Data extends from March 2013 (cycle 1 of the satellite mission) to May 2016 (cycle 33), with a repeat period of 35 days. Over this period, we use all altimeter observations located between 10°S-10°N and 105°E-140°E. Two tracks (#535 and #578) intersect the north of Sulawesi island and contain sampling points just off Bunaken Island. The data analysis is done in terms of sea level anomalies (SLA) computed from the 1-Hz altimeter measurements and geophysical corrections provided in GDRs products. The SLA data processing and editing are described in details in Birol and Niño (2015). The 1-Hz SLA data have a spatial resolution of ~7 km along the satellite tracks. In order to quantify the spatial variations of the regional sea level change in March 2013-May 2016, a linear trend model is applied (using a simple linear regression) to the individual SLA time series observed at the different points along the altimeter tracks crossing the area of interest. The trend is the slope of the regression (in $cm.y^{-1}$). The resulting 3-year sea level trend values can be represented on a map.

4.3. Results

4.3.1. Mortality rates per dominant coral genus

For all colonies, dead tissues were found on the top and upper-flank of the colonies, with the lower part of the colonies remaining healthy (Fig. 11). Mortality was not limited to microatoll-shaped colonies only. Round massive colonies were also impacted. On microatolls and other colonies that may have lived close to MLW, the width of dead tissue appeared to be around a maximum of 15 cm. Entirely dead corals were found in the shallowest areas. Dead tissues were systematically covered by turf algae, with cyanobacteria in some cases, suggesting that the stressor responsible for the mortality occurred few months earlier. There were no obvious preferential directions in tissue damage at colony surface as it has been previously reported for intertidal reef flat corals in Thailand (Brown et al., 1994).

Table 10: Mortality levels (mean ± standard deviation, n=6) of all corals for the 6 reef flat sites. The three dominant species were *Porites lutea*, *Heliopora coerulea*, and *Goniastrea minuta*. Several species and genus were found only once. Standard deviation is is not shown when only one measurement per type of coral could be achieved (i.e., one colony per site).

		Coral										
		Porites lutea	***Heliopora***	***Goniastrea***	***Acropora***	***Galaxea***	***Cyphastrea***	***Montipora***	***Porites cylindrica***	***Lobophyllia***	***Pocillopora***	*Mean*
	1	44±36	52±24						42±40			*46*
	2	39±16	18±8	100±0							100	*57*
Site	**3**	54±5		100±0	100±0	100	100					*58*
	4	20±17		100	25					100		*55*
	5	61±13	29±18			67		100±0				*85*
	6	52±23	70±8	46±51		100						*47*
	Mean	*44*	*42*	*82*	*45*	*89*	*100*	*100*	*42*	*100*	*100*	*58*

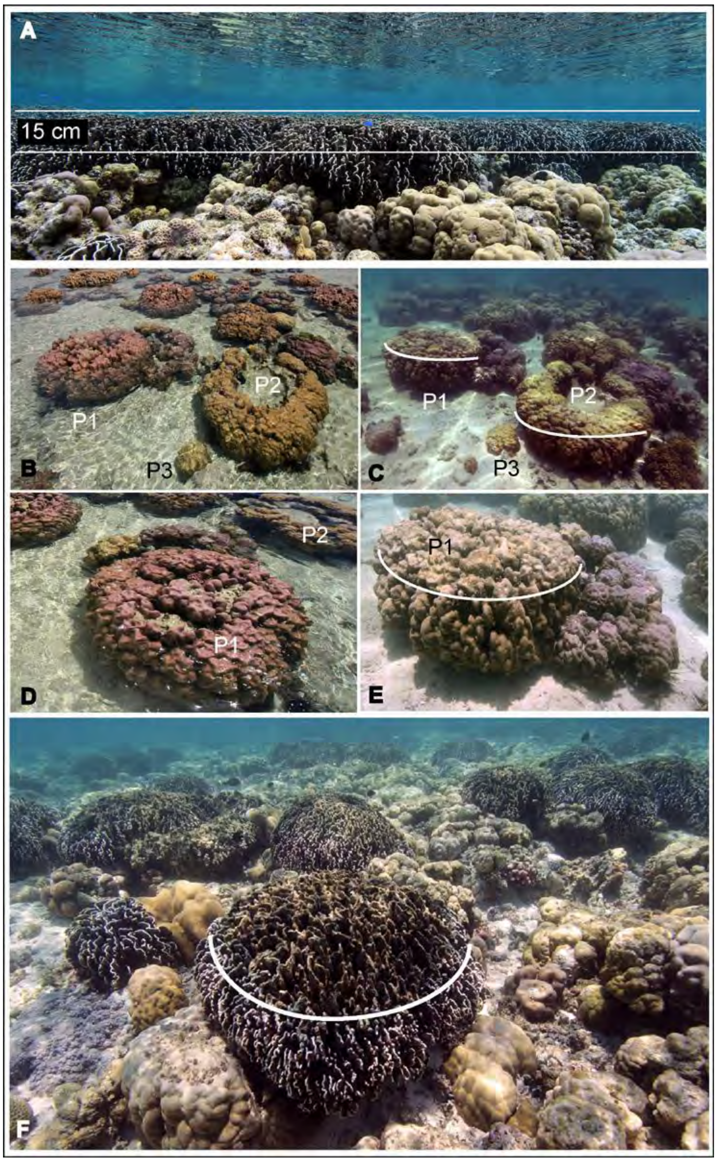

Figure 11: Bunaken reef flats. A: a living *Heliopora coerula* (blue coral) community in 2015 in a keep-up position relative to mean low sea level, with almost all the space occupied by corals. In that case, a 15-cm sea level fall will impact most of the reef flat. B: Healthy *Porites lutea* (yellow and pink massive corals) reef flat colonies in May 2014 observed at low spring tide. The upper part of colonies is above water, yet healthy. C: Same colonies in February 2016. The white line visualizes tissue mortality limit. Large *Porites* colonies (P1, P2) at low tide levels in 2014 are affected, while lower colonies (P3) are not. D: P1 colony in 2014. E: viewed from another angle, P1 colony in February 2016. E: Reef flat community with scattered *Heliopora* colonies in February 2016, with tissue mortality and algal turf overgrowth.

The six surveyed reef flat locations were dominated by *H. coerulea* and *P. lutea*, while other genus and species occurred less frequently (Table 10). When taking into account all genus, up to 85% of colonies were dead (Site 5). The average of mortality was around 58% all sites included (Fig. 2). When it was present *Goniastrea minuta* colonies were the most impacted, with a 82% mortality on average (Fig. 12). Highest mortalities were found on keep-up communities relative to sea level (Fig. 11).

4.3.2. Map of occurrences of mortality

The survey around the island revealed presence of mortality all around the island except the north reef flats where corals were scarce and encrusting (Fig. 12). The same coral genus as listed in Table 10 were impacted, but mortality levels differed depending on colony heights. When colonies were clearly below the present minimum sea level, they remained healthy (Fig. 11). The map of positive observations shows that mortality has occurred mostly along the crest, which is expected during sea level fall (Fig. 12). The survey suggests that nearly 163 hectares, or 30% of the entire reef system, has been impacted by some mortality. However, this does not mean that 30% of the reef is dead.

4.3.3. Absolute Dynamic Topography time series

The ADT time-series (Fig. 13) shows a significant sea level fall congruent with El Niño periods, at all spatial scales, although the pattern is not as pronounced at Indonesia-scale (Fig. 13). The 1997-1998 and the 2015-2016 years display the highest falls. The September 2015 value is the local minima, considering the last ten years (Fig. 13). The 8 cm fall in September 2015 compared to the previous 4 years, and the 15 cm fall compared to the 1993-2016 mean (Fig. 13) is consistent with the pattern of mortality following a maximum of ~15 cm width on the top of the impacted colonies that were living close to the mean low sea-level before the event (Fig. 11).

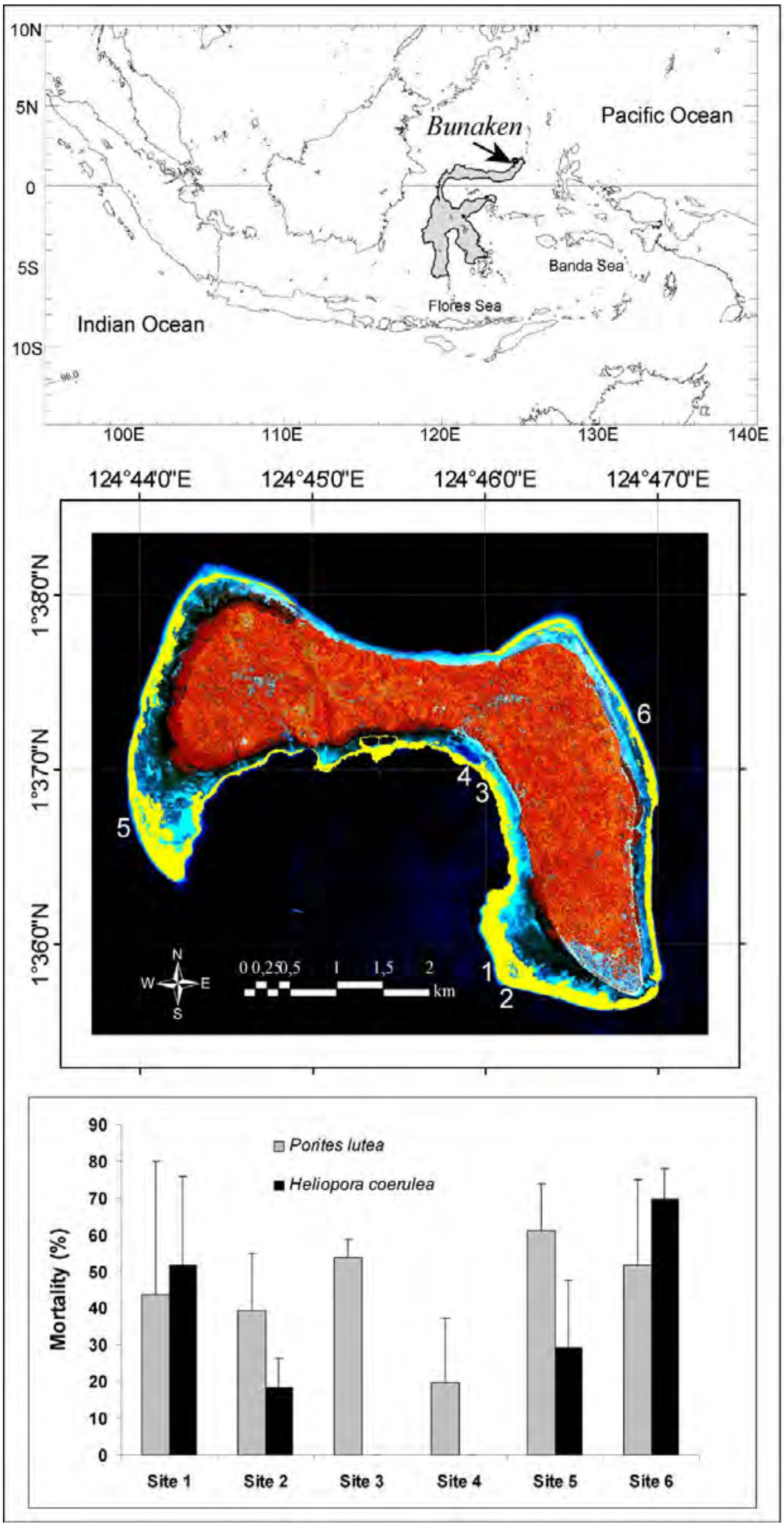

Figure 12: Top: Bunaken location. Sulawesi is the large island in grey. Middle: The yellow area shows where coral mortality occurred around Bunaken reef flats, with the position of six sampling stations. Dark areas between the yellow mask and the land are seagras beds. Blue-cyan areas are slopes and reef flats without mortality. Bottom: Mortality rates for the 6 sites for two dominant species *Porites lutea* and *Heliopora coerulea*. The latter is not found on Sites 3 and 4.

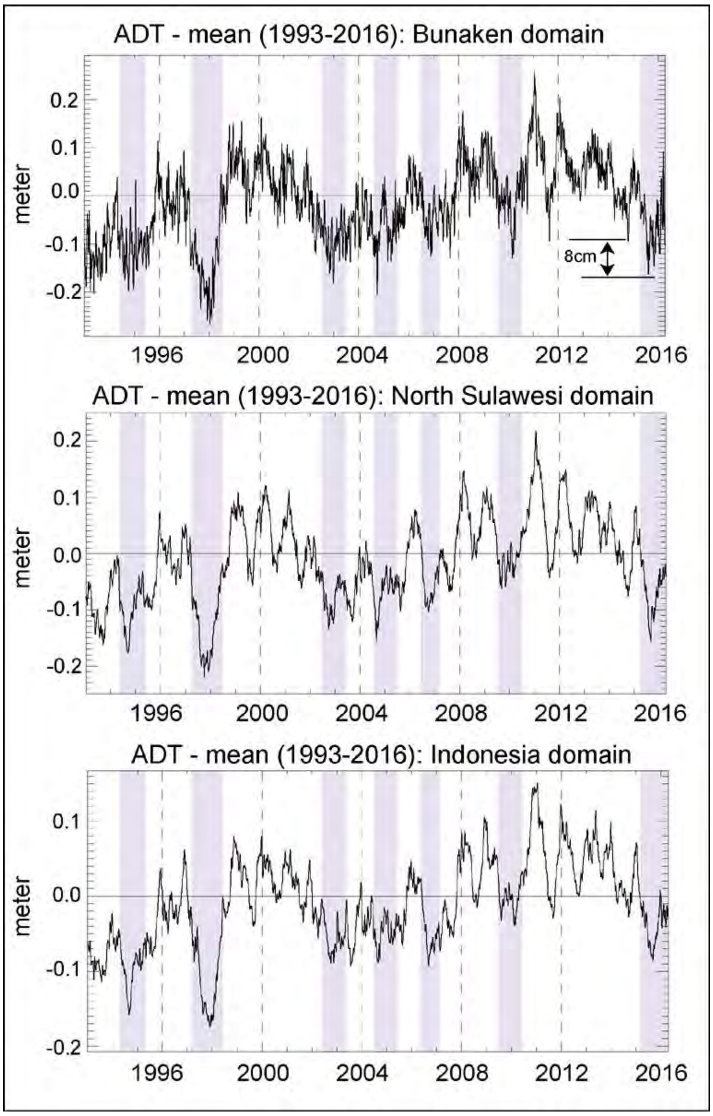

Figure 13: Time series of ADT, minus the mean over the 1993-2016 period, for Bunaken Island (top), North Sulawesi (middle), and Indonesia (bottom). The corresponding spatial domains are shown Figure 15. El Nino periods are depicted with light shadings (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). The September 2015 minimum corresponds to a 8 cm fall compared to the minima the four previous years, and a 14 cm fall compared to the 1993-2016 mean. The 1998 El Niño displays the largest sea level fall.

4.3.4. Sea Level Anomaly trends

SARAL/AltiKa data in March 2013-May 2016 are shown in Figure 14 for a small area that includes Bunaken Island (top) and a larger box (bottom) covering part of the western equatorial Pacific Ocean and Coral Triangle. A substantial sea level fall is observed around Bunaken Island, with values ranging from 4 to 8 cm/year (12 to 24 cm accumulated over 3 years, Fig. 14). Further analysis of the individual sea level time series indicates that the overall trend is explained, and accelerated, by the fall due to El Niño (not shown). This result agrees with findings from Luu et al. (2015) around Malaysia and can be extended to much of the Coral Triangle. The Figure 14 shows that this phenomenon is consistent over a large part of Indonesia and the warm water pool, with strong differences in sea level variations (up to -15 cm/year are observed between Asia and Micronesia, north of 5°N and east of 130°E).

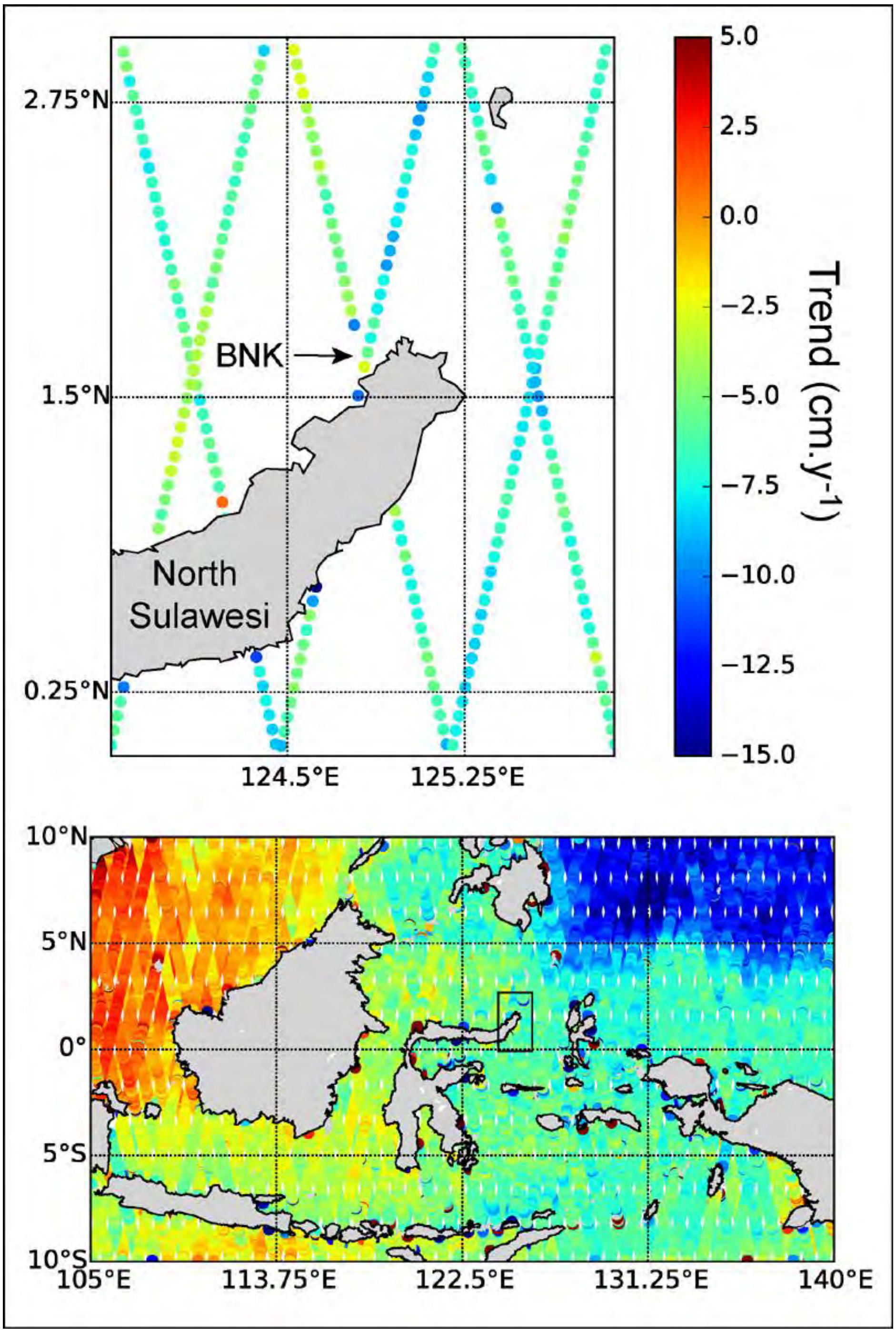

Figure 14: Top: Map of along-track SLA trend (in cm.year-1), 2013-2016, for the north Sulawesi area. The position of Bunaken Island is shown (BNK). Bottom: Map of along-track SLA trend (1-Hz), 2013-2016, for Indonesia. The domain on the top panel is the rectangle in the Indonesia map.

4.4. Discussion

We aimed here to document the spatial scale and the cause of an ecological event that could be easily overlooked when documenting the 2016 El Niño impact on Indonesian coral reefs. Many studies have emphasized the role of hydrodynamics and sea level on the status of the coral communities growing (or not) on reef flats (e.g., Hopley, 2011). Sea level variations in relationship to coral mortality on reef flats have also been previously reported, but here we emphasize, with altimetry data for the first time, that the 2015-2016 El Niño has generated such mortality, well before any bleaching. The exact time of the mortality remains unknown, but it is likely congruent to the lowest level in September 2015. The Figure 11 shows corals that were fine in May 2015 even when exposed to aerial exposure during low spring tide for several hours, during several days of spring tide, so we assume the mortality was due to several weeks of low water, including spring tide periods, corresponding to the temporal resolution of the altimetry observations. The aerial exposure could have led to tissue heating, desiccation, photosystem or other cell functions damage (Brown, 1997). It is possible that colonies could have look bleached during that period (Brown et al., 1994).

The various satellite Sea Surface Temperature (SST) products for coral bleaching warning available at http://coralreefwatch.noaa.gov/ do not suggest any bleaching risk in the Bunaken region before June 2016, hence the mortality we observed can not be simply explained by ocean warming due to El Niño. We also verified on http://earthquake.usgs.gov/that between the May 2015 habitat mapping survey and the February 2016 coral survey, no tectonic movement could generate such a 15 cm–uplift, with an upward shift of coral colonies relative to sea level as it has been reported in different places in the past, including in Sumatra, Indonesia after the 2004 Sumatra Earthquake (Meltzner et al., 2006). An uplift of that magnitude would be related to a significant earthquake, but there are no reports higher than a 6.3 magnitude earthquake (16^{th} September 2015, origin 1.884°N 126.429°E) in the north Sulawesi area for that period.

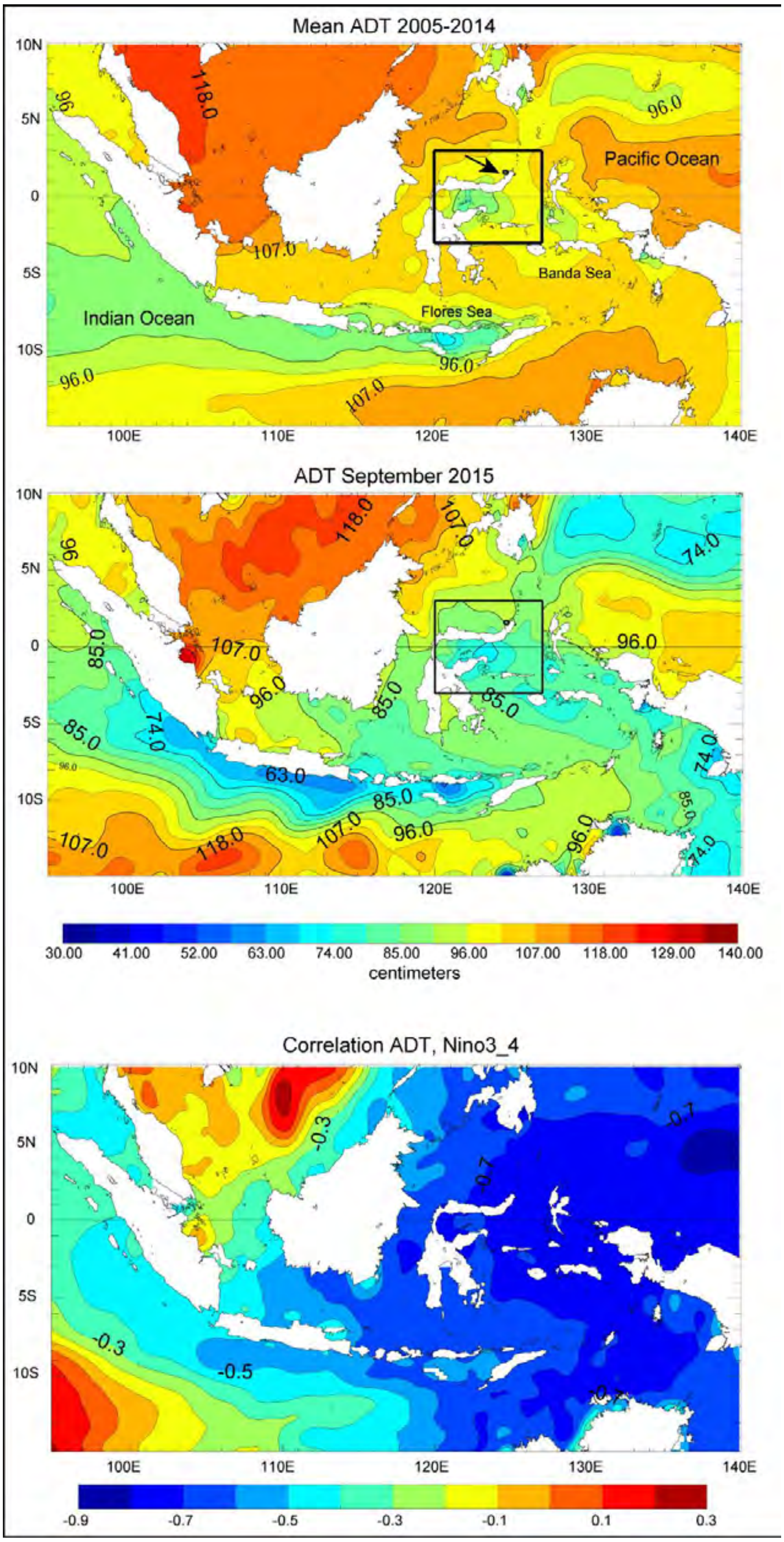

Figure 15: Top: Map of the 2005-2014 Absolute Dynamic Topography (ADT, in centimeters) average over Indonesia. Middle: Map of the September 2015 ADT mean value over Indonesia. The two squares indicate the domain just around Bunaken Island (arrow on top panel) and the Nino3-4 index (1993-2016, monthly average minus seasonal cycle).

Altimetry data have been seldom used to study coral reef processes, even in a sea level rise era that may affect coral reef communities and islands. They have been useful to assess the physical environment (wave, tide, circulation, lagoon water renewal) around islands and reefs (e.g., Andréfouët et al., 2001; Burrage et al., 2003; Andréfouët et al., 2012; Gallop et al., 2014), or explain larval connectivity and offshore physical transport between reefs (e.g., Christie et al., 2010), but this is the first time to our knowledge that altimetry data, including the new SARAL/AltiKa data, are related to a coral ecology event. Different measures of sea level and sea level anomalies confirmed an anomalous situation following the development of the 2015-2016 El Niño, resulting in lower sea level regionally averaging 8 cm in the north of Sulawesi compared to the previous 4 years (Figs. 13-15). Mortality patterns on coral colonies strongly suggests that sea level fall is responsible of the coral die-off that could reach 80% of reef flat colonies that were in a keep-up position relative to, usually, rising sea-level in this region (Fenoglio-Marc et al., 2012). The aspect of the colonies in February 2016, with algal turf covering the dead part (Fig. 11), is also consistent with a lowest sea level occurring few months earlier in September 2015.

While mortality due to sea level fall was characterized opportunistically in Bunaken NP, the impact remains unquantified elsewhere. However, we speculate that similar events have occurred throughout the Indonesian seas when considering ADT values for this region (Fig. 5). Particularly impacted by sea level fall could have been the stretch of reefs and islands between South Sumatra, South Java, the Flores Sea and Timor, and the domain centered by Seram island and comprised between East Sulawesi, West Papua and the Banda Sea. These areas have substantial reef flat presence (e.g., for the Lesser Sunda region comprised between Bali, Maluku and Timor islands, see maps in Torres-Pulliza et al., 2013).

Specifically for Bunaken NP, the event we have witnessed helps explaining long term observations of reef flat dynamics and resilience. Indeed, our surveys and historical very high spatial resolution satellite imagery show around Bunaken Island the fast colonization of reef flats by *Heliopora coerula* and by carpets of branching *Montipora* in the years 2004-2012, a period congruent to substantial rising sea level (Fig. 13) (Fenoglio-Marc et al., 2012). Rising seas has allowed these corals, especially fast growing and opportunistic like *H. coerula* (Babcock, 1990; Yasuda et al., 2012) to cover previously bare reef flats by taking advantage of the additional accommodation space. A similar process occurred in Heron Island reef flats in Australia, with an artificially-induced sea level rise due to local engineering work (Scopélitis et al., 2011). In Bunaken, and probably elsewhere in Indonesia and the Coral

Triangle, the 2015-2016 El Niño event counter-balances this period of coral growth with rising seas.

The ADT time-series (Fig. 13) suggests that similar situations have probably previously occurred, and almost certainly at least in 1997-1998, the highest anomaly on altimetry record. Reef flat coral mortality reported in the Coral Triangle as the consequences of bleaching in these years is thus most likely also the consequences of sea level fall. The discrimination between thermal and sea level fall-induced mortality could be difficult to pinpoint on reef flats, if surveys had occurred several months after the thermally-induced bleaching. In Bunaken NP, mortality due to sea level fall preceded by nearly 7 months the first occurrences of bleaching, reported in April 2016. The real impact of sea level fall could have been largely underestimated during all El Niño episodes and especially in Asia. The implications for coral reef monitoring in the Coral Triangle are substantial. Surveys that may have started in April 2016 may be confused and assigned reef flat mortalities to coral bleaching. In future years, monitoring SLA may be as important as monitoring sea surface temperature (SST). While there are several SST-indices specifically used as early-warning signals for potential coral bleaching (Teneva et al., 2012), there are no sea level indices specific for coral reef flats. However, several ENSO indices can help tracking the likelihood of similar events for Indonesia. The high correlation between the NINO3_4 index and ADT over the 1993-2016 period (monthly mean minus seasonal baseline, Fig. 6) shows this potential. Other indices, such as the Southern Oscillation Index (SOI, computed as the pressure difference between Darwin and Tahiti), or the Equatorial SOI (defined by the pressure difference between the Indonesia-SLP, standardized anomalies of sea level, and the Equatorial Eastern Pacific SLP) appears to be even more suitable over Indonesia and the Coral Triangle to develop suitable early-warning signals related to sea level variations.

4.5. Conclusion

This study reports coral mortality after a El Niño-induced sea level fall. The fact that sea level fall induces coral mortality is not new, but this study demonstrates that through rapid sea level fall, the 2015-2016 El Niño has impacted Indonesian shallow coral reefs well before that high sea surface temperature could trigger any coral bleaching. Sea level fall appear as a major mortality factor for Bunaken Island in North Sulawesi, and altimetry suggests similar impact throughout Indonesia. Our findings confirm that El Niño impacts are multiple and the different processes need to be understood for an accurate diagnostic of the vulnerability of Indonesian coral reefs to climate disturbances. This study also illustrates how to monitor local sea level to interpret changes in a particular coastal location. For Indonesia coral reefs, in addition to sea level fall depending on the ENSO situation, further changes can be expected, due to coral bleaching, diseases, predator outbreaks, storms and sea level rise (Baird et al., 2013; Johan et al., 2014). Considering the level of services that shallow coral reefs offer, in coastal protection, food security and tourism, the tools presented here offer valuable information to infer the proper diagnostic after climate-induced disturbances.

CHAPTER 5. ASSESSMENT OF THE RESILIENCE OF BUNAKEN ISLAND CORAL REEFS USING 15 YEARS OF VERY HIGH SPATIAL RESOLUTION SATELLITE IMAGES: A KALEIDOSCOPE OF HABITAT TRAJECTORIES

5.1. Introduction

Coral reefs are highly biodiverse and productive tropical ecosystems that provide numerous services to human populations. Coral reefs are also highly vulnerable to numerous natural and anthropogenic threats. The general consensus is that reefs worldwide have significantly degraded in the past decades due to pollution, overfishing, coastal developments and reclamations, physical destruction due to hurricanes, global warming and coral bleaching, and ocean acidification is a direct new threat triggered by increased concentrations of atmospheric greenhouse gases. While reefs have always been exposed to natural disturbances, the accumulation of natural and human-induced stressors may now impair their natural capacity to recover, even in remote unpopulated places (Pandolfi et al., 2003). Coral reef communities respond with different levels of sensitivity to these stressors reflecting both the normal environment and the site-specific history (Done, 1995; Wakeford et al., 2008; Scopélitis et al., 2009, 2010, 2011; Perry and Smithers, 2011). Monitoring programs attempt to document changes in the spatial distribution and composition of coral communities, and to understand dynamics of degradation and recovery at different spatial and temporal scales, from the global (e.g. Wilkinson, 2008) to the local scale (e.g. Done et al., 2007). Temporally, to provide a basis for reef management in light of disturbances and climate change, monitoring coral reef communities at a decadal temporal scale is necessary to understand and project their dynamics since managers also need to be cognizant of normal successional changes.

Unfortunately, despite numerous *in situ* monitoring programs now reaching two decades or more of data acquisition on habitat and benthic community dynamics and trajectories, how different reefs in different locations can cope with natural, direct human impacts (e.g. fishing) and climate change stressors remains difficult to predict. The main reason is the very high heterogeneity of situations in terms of biological communities, physical environment, isolation and connectivity with other reefs (and other ecosystems and watersheds), stressors, and finally management levels. Despite many modeling papers claiming recipes for managing reefs, their conclusion can not hold because of the very narrow range of situations they actually represent or the set of hypothesis used. The reality is that the vast diversity and complexity of coral reef situations worldwide remains a challenge. The question of whether any given reef will have the capacity to recover to their pre-disturbances state (engineering resilience, *sensu* Nyström et al., 2008), or evolve to a functionally different type of reef (ecological resilience) remains quite unsolvable considering the data presently available. In this context, we suggest that understanding the resilience capacity of any given reef requires first to investigate as much as possible the history of the reef and understand its specificities, and not only model its future. Furthermore, a reef is a complex mosaic of habitats, and virtually all *in situ* monitoring program based on, at best, few tens of stations captures only a fraction of the reef heterogeneity. While several studies have reported long term dynamics of coral cover for a number of reefs globally, the methodological caveats they provide (clearly stated in the papers) actually point to possible serious biases, including the fact that historical measurements were not always taken in the same places for a given reef (Bruno and Selig, 2007). Hence, spatially-explicit and georeferenced approaches are also needed to fully characterize the long-term response of a reef to disturbances (Scopélitis et al., 2011).

The challenge of reconstructing reefs and habitat trajectories synoptically across its entire mosaic of habitats is that, in most cases, there are no georeferenced quantitative information on what the reefs and their habitats looked like in the distant past, even only 30 years ago. The situation is worst 40 or 50 years ago. To complement infrequent and localized in situ observations, time-series of very high spatial resolution (1-4 meter) black-and-white and color aerial photographs combined with recent multispectral remotely sensed satellite images often provided the only source of information. These studies encountered significant issues, including: data mining, processing consistently a series of heteroclite images, lack of unambiguous invariant features to help the calibration and rectification of different images, and absence of ground-truth historical data. Few studies have attempted to reconstruct the trajectory of reef and habitats across multiple decades (Table 11). Yet, these studies could highlight engineering resilience across 35 years of disturbances (La Reunion Island, Scopélitis et al., 2009) or steady degradation due to destructive fishing (Madagascar, Andréfouët et al., 2013). In all cases, these studies have focused on shallow reef flats (less than 5 meters deep), where remote sensing is the most informative. No studies on deep (5-25 meters) forereef benthic changes have been done, or even can be considered feasible considering the intrinsic limitation of remote sensing in deep water (Maritorena et al., 1994) and often the more challenging environmental quality of images (waves and breaking waves foam may hide the reef underneath). Only structural changes have been highlighted on forereefs using aerial photographs, but the sites were also shallow spur-grooves configurations (Lewis 2002).

Indonesia is the country with the most extensive coral reefs worldwide (Tomascik et al., 1997; Done, 2011). Indonesian reefs also comprises the epicenter of marine biodiversity (Hoeksema, 2007), yet they have remained, comparatively to many coral reef-rich countries, infrequently studied, in part due to limited research permits allowed issued to study these reefs. This is slowly changing and Indonesia, as part of the broader Coral Triangle Initiative, should receive more attention in the future, including from remote sensing scientists. Due to high demographic and development pressure, and use of reefs for daily subsistence, reefs in Indonesia are severely threatened by human activities and climate change (Mangubhai et al., 2012). Like anywhere else on the planet, management and spatial planning of coral reefs in Indonesia need to be better informed with relevant habitat maps (Andréfouët et al., this issue), and, as discussed above, with better understanding of reef habitat historical trajectories. Therefore, as a staged activity to inform coral reef management in Indonesia using remote sensing, we aimed to trial for an Indonesian reef the feasibility of tracking the history of its reef flat dynamics. As part of the Indonesian Development of Space Oceanography project, Bunaken Island (North Sulawesi) was selected by the Ministry of Maritime Affairs and Fisheries.

The objectives of this study were to reconstruct the history of Bunaken Island reef flats using primarily a multi-sensor time-series of very high spatial resolution (2-4 meter) satellite images starting in 2001. We aimed to span 15 years of observations, considering: i) the main period of research activity in Bunaken Island, which is one of the most studied site in Indonesia, ii) the period of availability of multispectral very high spatial resolution images. It is also one of the first managed site, being part of the Bunaken National Park created in 1991. In doing so, we aim to verify how the coral communities of Bunaken Island have changed in 15 years, and, if they had degraded at some point, do they appear to recover and be resilient, and how?

5.2. Material and methods

5.2.1. Study site

Bunaken Island (BI) is located by 1.62379°N, 124.76114°E, off Manado city in North Sulawesi (Fig. 16). It is part of the Bunaken National Park (BNP) which was established in October 1991 and encompasses 5 islands, and is the main visited location in the park. BI is surrounded by a simple fringing reef system, comprising reef flats, several small enclosed lagoons and forereefs. The total extent of this ensemble covers 5.42 km^2.

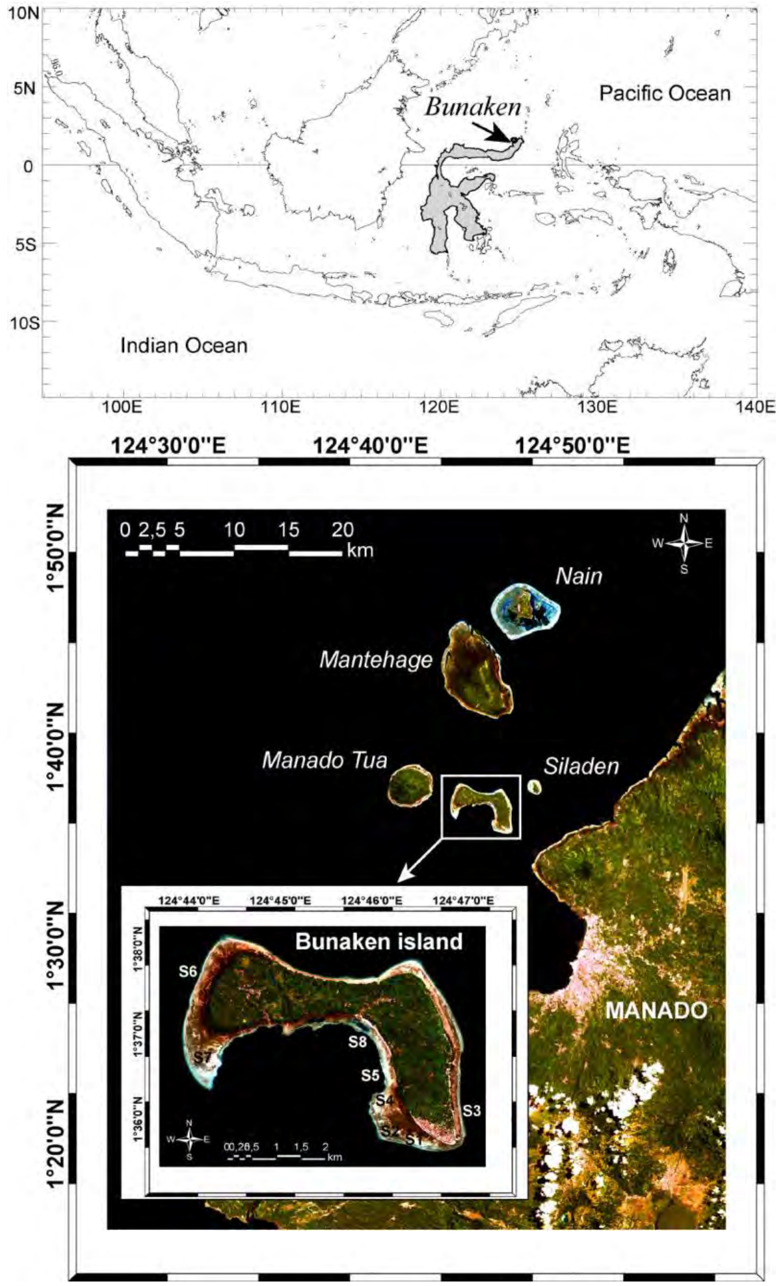

Figure 16: Location map. Sulawesi is highlighted in grey on the top panel. The five islands of the Bunaken National Park are shown. The location of the 8 scenarios discussed in the paper are shown in the Bunaken Island insert.

The forereefs include spectacular walls that have brought the dive industry to BI since more than three decades. The reef flats themselves are seldom visited by tourists, except one location dedicated to snorkeling activities. However, reef flats are systematically combed by the resident population at low tide to harvest crustaceans, mollusks and small fishes living in corals and seagrass beds. The gleaning activity occurs mostly on the south and east reef flats (EA, SA, pers. obs.) while villagers on small boats fish with handlines and sometimes spearguns around the island along the walls, and near high-current locations. Occasional fishing using nets was also witnessed and could happen anywhere around BI. Dynamite fishing was unheard of since more than 20 years around BI (EA, unpublished survey data), although it has been a common practice in the past (Erdmann et al., 2004).

Table 11: Selected publications on change detection of reef habitats across nearly two decades or more using high (Landsat: 30 meters), and very high (others: 1 to 4 meters) spatial resolution satellite sensors and aerial photographs.

Reference	Location	Type of images	Objective	Period	Method
Yamano et al. (2000)	Kabira Reef, Japan	Aerial photographs	Habitat changes	1973 - 1994	Photo-interpretation
Lewis (2002)	Barbados	Aerial photographs	Structural changes	1950 - 1991	Photo-interpretation
Palandro et al. (2003)	Carysfort Reef, Florida	Aerial photograph, IKONOS	Coral mortality	1981, 1992, 2000	Supervised classification
Houk & van Woesik (2008)	Saipan Northern Mariana Islands	Aerial photograph, IKONOS	Habitat changes	1940, 2004	Historical map, present time photo-interpretation and classification
Palandro et al. (2008)	Florida Keys, USA	Landsat TM, ETM+	Habitat changes	1984 - 2002	Supervised classification
Scopelitis et al. (2009)	Saint Leu-Reef, La Réunion	Aerial photographs, Quickbird	Habitat changes	1973 – 2006	Photo-interpretation
Scopelitis et al. (2011)	Heron Island, Australia	Aerial photographs, Quickbird	Coral growth	1972 – 2007	Classification
Andréfouët et al. (2013)	Toliara, Madagascar	Aerial photographs, Quickbird, Landsat	Loss of coral habitats	1962 - 2011	Photo-interpretation
El-Askary et al. (2014)	Hurghada, Egypt	Landsat TM, ETM+, OLI	Habitat changes	1987, 2013	Supervised classification
Nurdin et al. (2015)	Spermonde, Indonesia	Landsat TM, ETM+, OLI	Coral loss	1972 – 2013	Unsupervised classification

The tide regime is semi-diurnal, with a maximum spring tidal range that can reach 2.52 m. Bunaken Island is generally exposed to southwest wind from May to October, resulting in calm seas due to the short fetch between mainland and the island, and to northwest wind from November to February, which can be strong at time and generate large waves breaking on the west and north shores.

5.2.2. Remote sensing data set

The Table 2 lists all the images available for BI currently in the INDESO archive (Gaspar et al., this issue). All images offer a 4-band spectral resolution (B, G, R, NIR). This unique data set represents one of the most complete, high-quality, very high spatial resolution time-series available for research for any given reef on the planet, at the exception of a handful of research sites where periodic acquisitions have taken place (e.g., Heron Island in Australia, Kaneohe Bay in Hawaii, etc.). However, a substantial 5 year-long gap exists between June 2004 and November 2009 for which no suitable images could be located in any of the commercial sensor archives. Therefore, we also used all low cloud cover images from the freely available Landsat 5, 7 and 8 satellite archive, that could be identified before 2001 and between 2004-2009 if they helped confirming a polygon trajectory. However, these are 30-meter spatial resolution data only and these observations can be used only for changes over large areas.

BI is not covered entirely by all the images in Table 9. The southern part of the island was the most completely and frequently covered, and we focused on this part of the island for the analysis. This was also the most interesting part of BI due to its extensive reef flats and more diverse geomorphological zonations, including enclosed lagoons and sedimentary areas.

Two BNP surveys for habitat mapping, in May-June 2014 and May-June 2015 have identified more than 170 different habitats around BI from the inshore mangroves to the outer walls (see Chapter 3). The entire reef has been mapped considering the present time observations using a March 2014 multispectral (blue, green, red, near infra-red band) Geoeye-1 2-meter resolution image. The habitat polygon boundaries were set by photo-interpretation according to spectral (color) and texture appearance (Andréfouët, 2008) and labelled according to the typology of habitats inventoried *in situ*.

For the change detection analysis, images in digital counts (DN) were empirically processed to minimize radiometric differences between images (Andréfouët et al., 2001). Since we used an empirical approach applied to digital counts, no attempt was made to normalize between sensors the different bandwidth of each spectral band (as in Hu et al., 2001). First, dark pixel correction was systematically applied as a proxy for atmospheric corrections, using pixels from the nearby ocean away from any sunglint. Then, an empirical line correction (Karpouzli and Malthus, 2003) was applied using bright and dark substrates that appeared consistent across pairs of images (sand on beach and very dense intertidal seagrass beds). Images were processed sequentially, the last corrected image being used as a reference for the following, older, one. The 2014 Geoeye-1 image was the first reference used. Unlike other work in Indonesian reefs (Manessa et al., 2014), no depth correction was applied due to the narrow range of depth found on the reef flats and across the time-series. For one image acquired at high tide and in rougher sea conditions (2009 image), these procedures were inefficient to match the images to the 2014 image and to provide consistent bottom signatures. The image was not discarded from the analysis because the images were photo-interpreted, but different enhancements for visual interpretation had to be performed. No images were processed to remove sunglint effects (Hochberg et al., 2003), as it was not necessary due to the good environmental quality of the images (except for 2009).

Images were co-georeferenced (UTM WGS 1984, zone 51N) also using the 2014 Geoeye-1 image as reference for the other images. Numerous features on the reef edge and on land (house, wharf, roads, and building) allowed achieving a RMS inferior to one pixel in all cases, using 12 ground-control points.

5.2.3. Mining georeferenced historical in situ data

We searched the scientific and grey literature in English and Bahasa Indonesia on BI to identify relevant data sets for our purpose. We looked for historical reef flats descriptions and photographs that were precisely georeferenced. General description could bring some clues but can not be used for mapping and interpretation of changes. Authors were contacted when suitable data could be identified.

5.2.4. Image and habitat-scenario analyses

To identify using very high spatial resolution images changes that have occurred on reefs, understand reef habitat dynamics and discuss resilience, we followed a pragmatic strategy which was partly inspired by our previous work on coral reef change detection over long periods of time (Palandro et al., 2003, 2008; Scopélitis et al., 2009, 2011; Andréfouët et al., 2013). In particular, we have experienced that mapping systematically at pixel-level small changes across the entire reef by image radiometric differences can be difficult to thematically interpret due to radiometric noise (Andréfouët et al., 2001), imperfect radiometric inter-calibration of images (especially using different sensors), geometric mis-registration (especially with sensors of different resolution and able to acquire images obliquely from their fly path), and maybe more importantly, lack of *in situ* data across the reef (Scopélitis et al. 2009). In other words, many of the changes visible can be “false positive” (detected changes that are not actual changes) and/or very difficult to interpret ecologically speaking. Our interest here is in the detection of representative ecological changes that could have occurred on the reef to try to understand the processes at stake. Therefore, instead of working by computing image differences across the entire area and try to figure out what has happened, we followed a supervised “scenario-based” strategy that consists in identifying habitat polygons precisely described at present time (in 2014 or 2015) and displaying unambiguous series of changes across the image time-series. By identifying a variety of scenarios of changes across the reef system, we assumed that we could uncover representative trajectories of habitats across the studied period, and assess how BI responded to disturbances.

Practically, we compute the difference between pairs of images (e.g., 2014 image minus the 2001 images, or 2014 minus the 2004 image which offer complete coverage of the island) to identify strong radiometric differences across at least a decade (Fig. 17). Histograms of differences between different calibrated spectral bands visualize the level of changes. Interestingly two 2001 images were taken only 3 days apart. It is not expected that the reef has changed in 3 days, but images are taken in different geometric and environmental conditions. A perfect calibration would lead to a null difference across the entire image and the histogram of image difference would be a spike centered at zero. In practice, the calibration is not perfect, and after radiometric normalization, the histogram of image difference provides the uncertainty, or noise, that can be expected with our methods (Fig. 17). Similar approach to quantify noise using images taken few days apart was discussed in Andréfouët et al. (2001). It can be postulated that differences higher than the uncertainty limit detected with the couple of 2001 images correspond to real changes. The further away from this limit the less ambiguous the detection of changes (Fig. 17).

Unambiguous changes with high radiometric difference (positive or negative) can be identified on the histogram of the difference image. These can correspond to, for instance, a temporal shift from a dark polygon to a bright one, and vice-versa. Other intermediate, less contrasted, cases could obviously also occur (Fig. 17). Areas of high difference identified by thresholding the difference image were overlaid with the habitat polygons to select a variety of behavior. Eventually, 8 polygons were selected because of their clear evolution and because they provided trajectories representative of the variety of patterns we could identify (Fig. 18). These clearly changing polygons were systematically revisited to remap by photo-interpretation the content of these polygons across time, and assess if the changes were systematic across the entire polygon or patchy within the polygon.

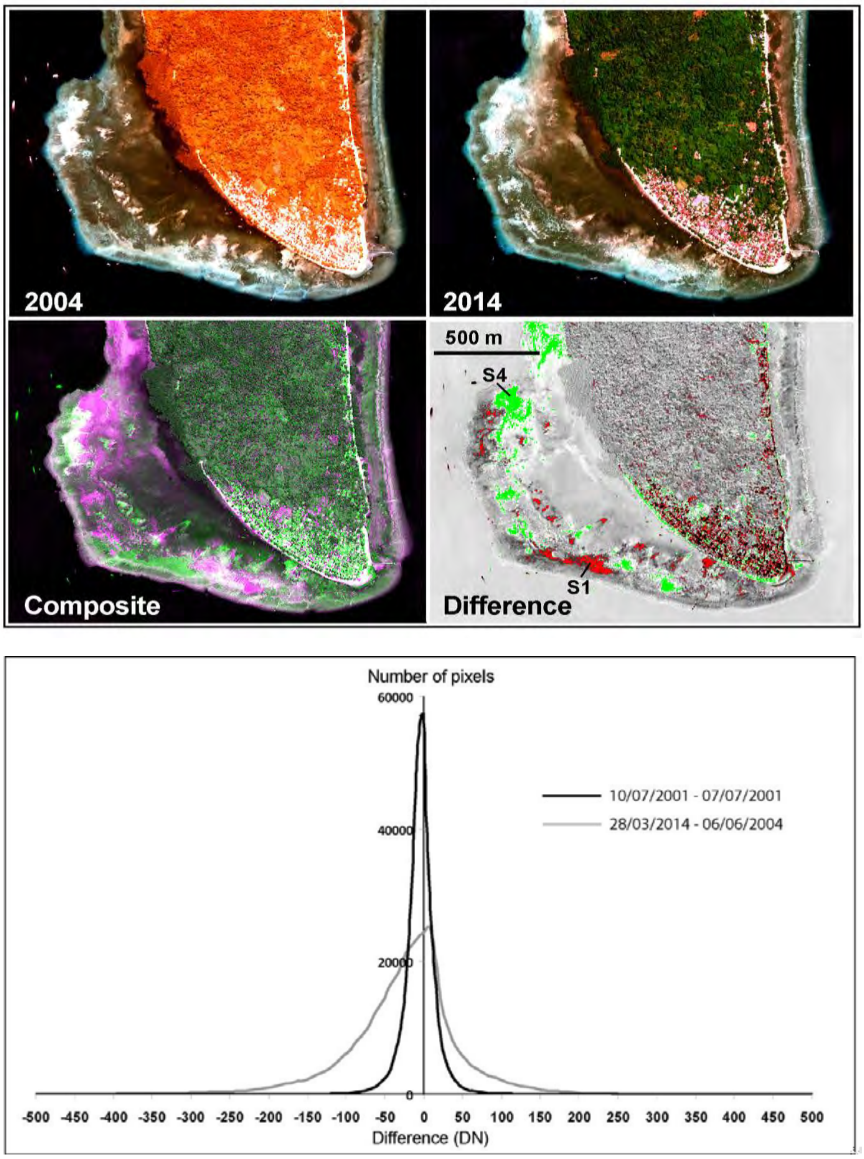

Figure 17: Top panel: Image difference and identification of areas of high radiometric changes. The IKONOS 06/06/04 and Geoeye 28/03/14 images are shown for the southeast corner of Bunaken Island displaying wide reef flats. Images have been co-registered and the 2004 image is radiometrically corrected against the 2014 image for the lagoon features. Note the differences in land vegetation that are not considered for this correction. A color composite using the green band of each image shows changes from dark to bright in pinkish color. Greenish colors highlight changes from bright to dark. Note that these two trends can occur very close spatially. Neutral white to dark grey areas are no-change areas. Thresholding the difference image highlights areas of dramatic unambiguous changes from which scenarios are selected. The locations of Scenarios S1 and S4 are shown, respectively representing a shift from bright to dark and a shift from dark to bright for wide areas less than one kilometer apart. The bottom panel shows the histogram of image difference (also Band 2) for two images only 3 days apart in July 2001, and for the 2004-2014 couple. Since the reef can not have experienced significant changes on the ground in 3 days, the narrow histogram for the 2001 images provides the level of noise on the empirical calibration of two images and thus the level of uncertainty in detecting changes using image differences. In contrast, the wider 2004-2014 histogram reveals more profound asymmetrical changes.

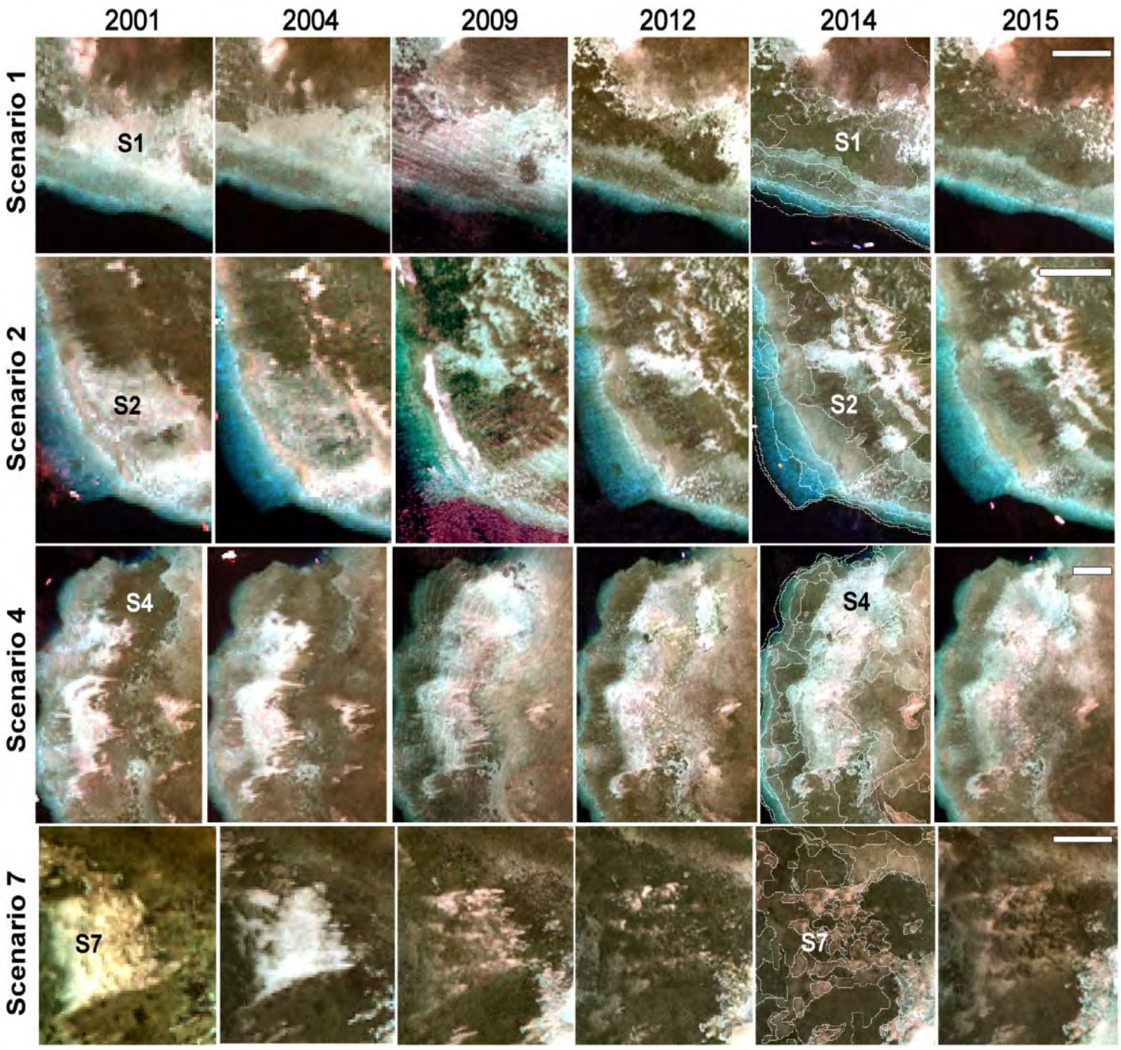

Figure 18: Image time series for 4 of the 8 scenarios (see Table 12) illustrating progressive or rapid changes. Exact dates are provided Table 2. The white scale-bar on the upper part of the 2015 panels represent 100 meters. The letters S1, S2, S4 and S8 are positioned on the area of interest. The outlines overlaid on the 2014 images are the boundaries of homogeneous habitat as defined by ground-truthing in 2014 and 2015. These polygons represent the limit that is considered to compute surface areas in Figure 20.

5.2.5. Interpretation of changes

To be able to discuss resilience, changes visible on selected polygons had to be thematically interpreted taking into account the nature of habitats that have disappeared/appeared. To identify and give a name to these unknown lost habitats, we have to rely on their spectral signatures. If $S_y(p)$ is the spectral signature (mean and standard deviation in each multispectral band) of polygon p in year y, to qualify the k-year trajectory between year y and previous year y-k of a polygon p_i, we relied on:

1. Ground-truthing of polygon p_i in year y, with in effect y=2014 or 2015
2. If historical data available, ground-truthing of polygon p_i in year y-k
3. Using the signatures, by ground-truthing other polygons p_j in year y characterized by:

$$S_{y-k}(p_i) \approx S_y(p_j)$$

4. or, using the differences in signature for p_i across time, ground-truthing of other polygons p_j in year y characterized by $S_y(p_i) - S_y(p_j) \approx S_y(p_i) - S_{y-k}(p_i)$, with in effect y = 2014 or 2015.

In practice, the easy solution in point 2 was never possible. For points 3 and 4, these simple methods assume that images are relatively well radiometrically inter-calibrated in time in remote sensing reflectance or digital count (DN). To estimate if the signatures between polygons were close enough, instead of using a measure of distance, we used the interactive nD-visualizer tool in the ENVI© software. This convenient tool provides a 3D representation of the pixels of each polygon in the RGB spectral space, allowing to visualize the spectral overlap between polygons. An example is provided in the results section.

5.3. Results

5.3.1. Image time-series quality and correction

The computed differences between images suggested a good relative inter-calibration of images in most cases, with differences between the ocean and stable areas (dense seagrass, beach) between 4 and 20 digital counts (DN). The histogram of differences between spectral bands for the two 2001 images yielded an absolute uncertainty limit at around 100 DN, although 97.5% of the histogram is included between -50 DN and 50DN interval (Fig. 2). These values set a noise limit for detecting actual changes with any confidence. However, changes could reach up to -400 and 300 DN between the 2001 (or 2004) and the 2014 images (Fig. 2). To identify areas of large changes, we thresholded the difference images, with thresholds at -150 and 150 DN, to map the highest positive and negative changes. We created thus 2 masks respectively showing the brightening and the darkening of the reef flats. High differences were also attributed to a number of artifacts: boats, breaking waves, new roads and houses, vegetation growth along the shores, and 1 or 2 pixel shifts in the geo-correction process between some of the image pair that created high differences in the village areas. Between some of the pair of images, like in 2001, the effect of tide was visible, resulting in larger systematic differences between images (Fig. 2). Eventually, the selection of polygons was made to include the largest differences, either positive or negative. We additionally included 2 scenarios with less striking changes between 2001 and 2014, but nevertheless high between some of the intermediate image pairs. These scenarios could point to shorter changes or oscillations in habitat trajectories.

5.3.2. Historical data search

The search for georeferenced reef flat historical data was disappointing for what was theoretically one of the most studied sites in Indonesia in the past decades. Unfortunately, the most promising and critical data sets in the form of *in situ* photographs described in Newman et al. (2007) and covering the years 2001-2004, appeared to be lost and unavailable (Newman, pers. com.). Fuad (2010) provided a limited number of useful descriptions with transects crossing the reef flats in 2009. Contacted scientists that visited BI had photographs, especially for the crests between reef flats and forereefs, but could not provide their precise locations, but rather dive site names which is not precise enough for our needs. All other published relevant and data rich monitoring or biodiversity studies did not cover shallow reef flats (e.g., Turak and DeVantier, 2003). As such they represent well the usual unfortunate bias of coral reef studies towards deeper forereefs that are investigated using SCUBA. Some relevant studies investigated nearby islands in the park, but not BI (Fox et al., 2003; Runtukahu et al., 2007). The outcome of this search was that very little useful scientific data could be located to help interpreting the changes on reef flats between 2001 and 2015 (i.e., Fuad, 2010).

5.3.3. Changes for selected polygons

The Table 12 describes the specifics of each scenario deemed representative of the changes occurring on the reef and our interpretation. Pictures illustrating the 8 polygons in 2014 or 2015 are shown Figure 4. The Figure 5 presents variation of surface areas for the eight scenarios. In Figure 5, the curves were not linked between 2004 and 2009 considering the lack of images. This gap proves to be very problematic to identify precisely the beginning of the changing trend in most cases. An exponential or polynomial curve was fitted to the data to visualize what could be the continuous trajectories (Fig. 5), but we do not pretend these models represent reality. Other trajectories between 2004 and 2009 remain possible including more abrupt changes, especially for scenarios 1, 2, 4 and 7. Nevertheless, we wanted to assess if all scenarios could be modeled by a consistent type of curve. It turns out not to be the case (Table 12). All curves yielded a $r^2 > 0.95$.

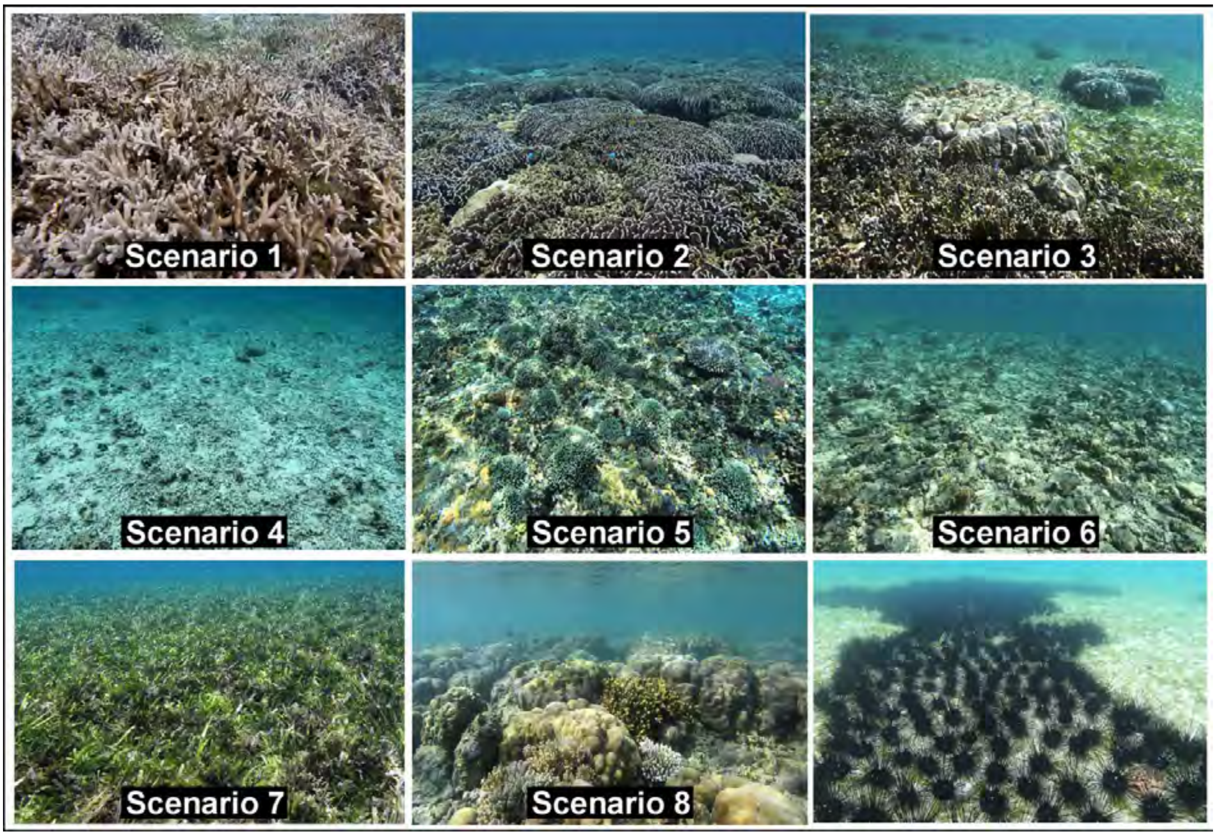

Figure 19: In situ pictures of the habitats present in 2014 or 2015 for each of the scenario, thus illustrating the terminal state of the 2001-2015 trajectories. Scenario 3 picture is taken at the edge of the growing Montipora thicket, that has started to surround *Porites* colonies. For scenario 5, the picture shows one of the last pocket of coral with *Montipora* growth, small massive colonies, and encrusting corals as it could have been at the beginning of the time-series in 2001, albeit with higher coral cover. The last picture illustrates the abundance of *Diadema* urchins as they regroup during day time (see Discussion).

In all cases but one, trajectories were showing only one trend of change (stable, decreasing or increasing coral cover), without oscillations or alternate temporary trajectories. Spikes in the change trend were mostly attributed to image processing noise, especially for images only few days apart, although in some cases, they were unambiguous changes due to a transient patch of different cover over a short period of few months (e.g., blooming patch of cyanobacteria that we have frequently seen in 2014 and 2015).

Table 12: Description of the identified scenario. "Growth" implies here horizontal expansion. P2-4 means polynomial model order 2-4. Exp.: exponential. Location of the scenarios is shown Figure 16.

Scenario	Type of scenario and area of polygon	Comment	Model
1	Coral growth (*Montipora*) 15000 m^2	From pavement-rubble to coral thickets dominated by branching *Montipora.* A dominant pattern of the southeast reef flat.	Exp.
2	Octocoral *Heliopora coerula* growth 5000 m^2	From pavement-rubble with scattered *Porites* to compact *Heliopora* colonies. A frequent pattern, patchy on all sides of the island. Absent from the north.	P3
3	Coral growth (*Montipora*) 25000 m^2	From banks of fine size rubble to coral thickets dominated by branching *Montipora.*	P4
4	Coral loss (*Montipora*) 33000 m^2	From coral (presumably *Montipora* thickets) to pavement and rubble	P4
5	Coral loss (*Montipora-Acropora-others*) 24000 m^2	From a mix community of coral to rubble and pavement with scattered corals Along the crest of one sector of the island only, north of scenario 4.	P4
6	Coral loss or rubble bank erosion 11500m^2	Uncertain initial conditions, finish as rubble field with blocs. Rare pattern, only on the northwest coast.	P2
7	Sand loss, colonized by seagrass 25000 m^2	From sand to seagrass. Represent wide areas of the south reef flats mid-section. Also present are loss of seagrass replaced by sand in the same area.	P2
8	Coral stability (*Porites*) 17000 m^2	*Porites* remain dominant with some darker variation probably due to soft coral appearances. *Porites* in 2014-2015 are around meter scales, with some colonies of soft corals. A wide pattern on most of the reef edge.	P2

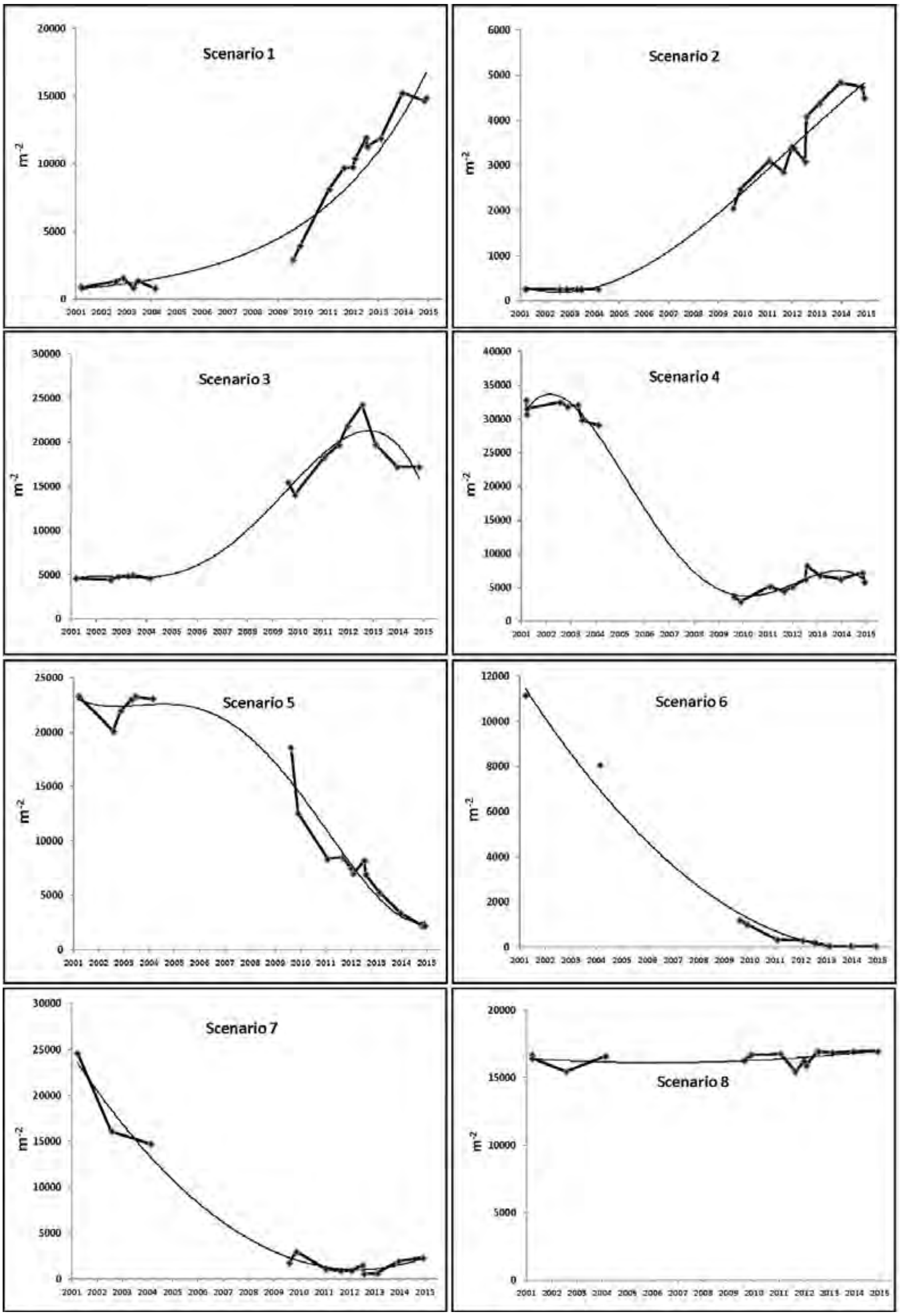

Figure 20: Changes of surface area (in square meter) of the focal habitat for each of the 8 selected scenarios (see Table 12). Points represent data from image interpretation. They are joined by straight lines except for the 2004-2009 gap for which the trajectory in uncertain. The continuous curves are exponential or polynomial fitted curves representing what could be a continuous trajectory based on existing data. See text for details and type of curves in Table 12.

5.4. Discussion

5.4.1. Towards an ecological view of changes using VHR images

This study highlighted, using a unique time-series of very high spatial resolution images, reef flat communities that are dynamic, with contrasted changes occurring across the reef at short distance. We applied here a semi-quantitative scenario-based approach to identify representative habitat trajectories and discuss if Bunaken Island reef habitats are resilient. We quantified the changes for selected polygons and identified qualitative scenarios, but did not try to interpret changes throughout the entire reef. This choice was dictated by previous experiences where all changes seen on the reef using per pixel mapping method can be difficult to interpret and are not all ecologically meaningful. While automatic detection of changes was straightforward (Fig. 17), their interpretation was not and thus we aimed first to characterize a relevant typology of changes. However, if we postulate that differences above the 100 DN threshold identified with the 2001 pair of images correspond to real changes, then 17% of the extent of the reef has changed between 2004 (first full image coverage of the Bunaken reef) and 2014 (Fig. 17). This is likely too conservative as 97.5% of the 2001 images difference was between -50 and 50 DN. With these values, up to 35% of the reef has changed between 2004 and 2014. The histogram of the differences between 2014 and 2004 shows a skewed distribution towards negative values, demonstrating a "darkening" of the reef from 2004 to 2014. We attribute this general trend to seagrass growth actually, thus a pattern represented by Scenario 7. An assessment of the dynamic of seagrass in Bunaken will be discussed elsewhere, as we focus here more on the coral habitat dynamics.

This study was also inspired by Kennedy et al. (2014) who discuss the value of the Landsat time-series to study ecological changes in a manner that corresponds to the view that ecologists can have with field study. Ecologists study in the field continuous changes influenced by natural and anthropogenic processes that interact at multiple spatial and temporal scales. In contrast, users of high spatial resolution (30 m for Landsat) historical remote sensing data usually see the world as snapshots, sometimes months or years apart, with often dramatic changes. It was thus typical to draw inference from incomplete temporal characterizations of the target dynamics, and thus limit the assessment to broad-scale, dramatic events (Kennedy et al., 2014). The Landsat 7 and 8 suite of images is authorizing since 17 years a shift towards an ecological view of changes more in line to field ecologist perception of ecosystem dynamics. Here, we intended to achieve the same shift with a unique time-series of very high spatial resolution data (2-4m). The ambition is only partially achieved. While we visualize changes unfolding every year during part of the studied period (Fig. 20), we unfortunately still have to deal with an incomplete characterization between 2004 and 2009, a period where dramatic changes have occurred. And of course, the years before 2001 are not described in any way, while they also have defined what the 2001 status was. However, the potential is clear and we show here the value of having annual, or every 2-year, coverage of reefs at very high spatial resolution to characterize resilience as ecologists could do in the field.

5.4.2. A kaleidoscope of habitat trajectories

The Figures 3-4-5 highlight a variety of behaviors found for polygons of habitats changing drastically between 2001 and 2015. All polygons were ground-truthed in 2014 or 2015, hence we know unambiguously in which state is each polygon at the end of the time-series (Fig. 19). Conversely, we had no information indicating the situation at the beginning of the time-series, but spectral similarity with patches of habitats present in 2014 helped finding out the most likely initial state (Fig. 21). The historical status can be sometimes inferred by contextual information: for instance, a seagrass bed is nowhere found on Bunaken Island reef crest, hence dark patches present on the crest are either dominated by coral, soft coral, or hard substrate colonized by algal turf based on 2014 surveys. However, due to the spectral similarities between habitats that can be of different nature (see Andréfouët et al., 2004), uncertainties may remain. It is impossible to decide which of these patches of live coral, soft coral and substrate with turf was actually present, and no contextual information can really help.

Factoring out one initial state *vs* the other is a difficult task that may require taking into account many additional field clues (such as type of rubble, their level of cementation, level of recruitment, colony sizes, current, differences in habitat that are spectrally similar, etc.). But it is not always guaranteed. Also, it is important to integrate facts and processes that may have occurred before 2001 such as the 1998 El Niño or destructive blast fishing. However, all scenarios, but one (Scenario 6), are pretty clear in their initial conditions (Table 12). Indeed, the scenario 6 on the west side of the island suggests, due to its signature, the presence close to the crest of an initial small patch of branching, carpeting, corals that vanished slowly with time. The image series is not as complete as other polygon but it suggests a linear trend (Fig. 20). However, similar patches in 2001 have remnants of their initial coverage in 2015 that we could visit. They were old cemented branching coral rubbles covered by cyanobacteria and turf algae with limited coral growth. The level of cementation suggests that the initial patches in 2001 may have been already in a similar rubble state with a dark turf/cyanobacteria complex or soft coral taking over. This would explain a regular rate of erosion of the initial patches by wave action during the summer months. The erosion may also have been on-going for already few years before 2001. The presence of bank of rubble and small blocs on this side of the island would not be surprising considering a possible storm from the west, or the effects of destructive dynamite fishing in the late 1990s, as it is described by Fox et al. (2003) on Manado Tua, the island facing this site. However, this remains a hypothesis.

Unfortunately, the time-series in Figure 20 suggests that the 2004-2009 period was critical in initiating changes. Quite frustratingly, we do not have any image data for this period to assess if the changes were progressive as suggested by the theoretical fitted curve (Fig. 20), or more abrupt especially for Scenarios 1, 2 and 4. Errors can be made in interpreting the time series here (Kennedy et al. 2014). The Landsat time-series provided cloud-free images of value only up to November 2005, which suggested similar conditions as in June 2004. After November 2006, the banding present in Landsat 7 images due to the scan line corrector problem prevented imaging the south of Bunaken most of the time. Both progressive and fast changes seem possible between 2004 and 2009 for all scenarios. Only Scenario 1 on *Montipora* coral colonization is marked by a late and sharp change. It is the only scenario where an exponential curve is fitting better than a polynomial curve. For other scenarios the ambiguity in the start, and thus in the speed of the changes, does not help identifying the cause of these changes.

Three scenarios illustrate coral colonization of previously bare substrate. Scenario 1 (Figs. 18 to 20) suggests a fast increase (~2200 m^2 y^{-1}between 11/2009 and 03/2015) of carpeting *Montipora* with some *Acropora* starting around 2008-2009, Scenario 2 (Figs. 3 to 5) suggests a slower (~500 m^2 y^{-1}between 11/2009 and 03/2015) but steady increase of *Heliopora coerula* with an uncertain starting date but which could be also 2008-2009. Scenario 3 (Fig. 20) suggests a fast increase (~3000 m^2 y^{-1}between 03/2010 and 11/2012) of carpeting branching *Montipora* but with a very uncertain starting date. This scenario is also marked by the only change of regime in all scenarios, with a decrease in cover (~3000 m^2 y^{-1}between 11/2012 and 02/2015). The reason of fast and localized growth could be explained by sea level rise in this region (Fenoglio-Marc et al., 2012), which offers additional accommodation space for corals to grow if they were previously vertically limited. Scopélitis et al. (2011) have quantified using remote sensing the fast colonization of bare substrate by corals in Heron Island after an artificially-induced local sea level rise. However, growth did not occur everywhere in Bunaken shallow flats, including a narrow moat that borders the site of Scenario 3. But it seems from the imagery that new growth occurred only on areas slightly elevated due to previous rubble deposit. Hence, these areas could have been indeed very limited in their possibility of vertical growth until sea level rise offered enough period of submersion for corals to grow. Nearby deeper areas, void of corals, remained the same way.

The Scenario 2 (Figs. 18 to 20) illustrates the colonization by *Heliopora coerula*. This octocoral, often called the "blue coral" is missing from the coral check list provided by Turak and DeVantier (2004). This can be explained by their surveys focusing on forereef slopes only. However, *H. coerula* was not reported also for earlier shallow studies (Newman et al., 2007). This is a common species in the region (Tomacsik et al., 1997), so we believe it was likely present early, but we suggest that this fast growing, opportunistic species has expended its Bunaken range in the 2001-2015 period. Same observations was made in Japan at Shiraho Reef in Ishigaki Island after the 1998 bleaching (Harii et al., 2014). Scenario 2 illustrates the colonization of one entire large polygon by this species, but in 2014 and 2015, it was also ubiquitous on all reef flats except in the north of Bunaken. *H. coerula* is also present in seagrass beds as isolated sub-meter-sized colonies, especially in the southwest large reef flat.

The Scenario 7 (Figs. 18 to 20) illustrates the general spreading of seagrass beds that we observed on all sides of the island except the north from 2001 to 2015. The bright sandy area of the initial 2001 image slowly decreases and gets entirely covered by seagrass. The time-series of images is not as complete as for other sites, but it suggests a progressive change, with constant colonization by seagrass. Seagrass beds inshore were the densest and the most stable of habitats on the image. Some patches, dominated by *Enhalus acoroides* are exactly similar in shape between 2001 and 2015.

Coral habitat areas which appear unstable, moving but with constant areas on the image (Scenario 8, Fig. 20) are predominantly located on the outer edge of the reef. They are reef flat and gently sloping crests before the drop-off, with dominance of *Porites lutea* and very diverse communities respectively. The polygon of Scenario 8 is dominated by massive and micro-atolls, from sub-meter to meter-scale, colonies of *Porites lutea* (Fig. 20). These corals are resistant to physical breakage unlike the fast growing branching corals. In 2014-2015, it was a healthy zone, suggesting that if some disturbances have affected them, they have fully recovered, and were not recovered by soft coral or algae.

The most striking pattern that we found from our 8 scenarios is the complete opposite trajectories between polygons only few hundred meters apart (Fig. 17). Above, we discuss the area of coral growth, but Scenario 4 and 5 illustrate respectively the loss of *Montipora* (as we identified it, see Fig. 21) and the loss of a more diverse community close to the crest. Scenario 4 is striking with a complete shift between 2004 and 2009 over a large area of corals (30000 m^2) (Fig. 18), but it remains ambiguous in terms of timing and speed of coral loss. Scenario 5 suggests a decrease initiating in 2007-2009, although we cannot rule out a slow progressive loss between 2004 and 2009. To identify the cause of mortality of these shallow coral communities, we can review the usual suspects described in the literature and rank them by order of increasing likelihood. Decrease in shallow coral communities could be explained by: disease, decrease in water quality, physical damage (impact by dynamite fishing, tramping, gleaning or boat impact), predation (by crown of thorns seastar -COTS- outbreaks), physical damage by storms, high sea surface temperature-induced bleaching, sun-induced damage, or sea level fall (Brown, 1997). While we can list possible factors of coral loss, we also have to reconcile them with the reef flats sections few hundred meters away (see Fig. 17) that have gained corals in the same period.

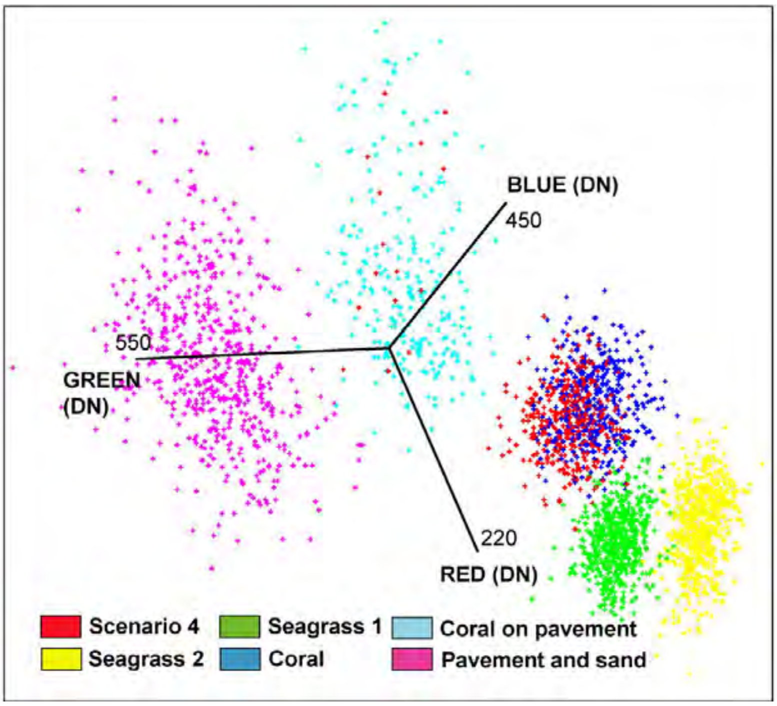

Figure 21: Identification of the initial state of Scenario 4 by comparison with the signatures of known habitats surveyed in 2014. The red pixels, corresponding to the initial state of Scenario 4 for which no ground-truthing was available in 2004, merge into the habitats identified in 2014 as *Montipora*-dominated thickets. They avoid dark seagrass beds signatures, and few points merge with the coral and pavement habitat. Maximum values for each spectral band (in digital counts, DN) are indicated on each axis.

COTS have been widespread in Bunaken in the studied period but especially in 2007 (Tokeshi and Daud, 2011). I have participated in the collection and destruction of ~70.000 COTS during the summer 2007. However, the study of the feeding preferences of COTS in Bunaken at that time suggests they avoided branching *Acropora* corals and *Montipora* (Tokeshi and Daud, 2011), which is probably the community that filled in 2001-2004 the dark patch in Scenario 4 (Fig. 21). Instead, Bunaken COTS in 2007 favored preying on massive corals, but Tokeshi and Daud (2011) looked at the east side of the island, where COTS densities were low. COTS populations at outbreak-density could result in higher competition for the remaining coral and the feeding on branching corals on the central part of the island. This is possible because in 2014 we have observed COTS feeding on *Montipora* branching framework near the Scenario 1 location. The trend shown for Scenario 5, considering its more diverse communities, is also compatible with destruction by COTS than Scenario 4. This area is also where we saw the highest densities of COTS in 2014-2015 even if it was far from reaching outbreak levels (>25 individuals per hectare, Baird et al, 2012). To summarize, the 2007 outbreak of COTS can potentially explain coral loss in scenarios S4 and S5, especially if they were feeding on branching *Montipora* and *Acropora*. However, it remains unclear why other areas nearby gained corals during the same period of time if COTS were active.

Coral bleaching has also occurred in Indonesia during the studied period, especially in February-June 2010 (Guest et al., 2012) but Bunaken was not impacted considering the oceanic conditions in north Indonesia (Wouthuyzen et al., 2015). Bleaching also occurred in 1998 following a strong El Niño event, but it was poorly documented in Indonesia. Bunaken in 1998 could have suffered from bleaching, although local strong current conditions and frequent upwellings should temper the effects of sea surface warming (DeVantier and Turak, 2004). Ampou et al. (submitted, see Chapter 4) recently show the effects of sea level fall on Bunaken corals. The 2015-2016 El Niño, the strongest on record, impacted in September 2015 shallow corals on 30% of the reef system with a sea level fall of about 10 cm, itself less important than in 1998. Sea level in 1998 indeed also dropped (Ampou et al. submitted, Chapter 4), and coral mortality on reef flat was more than likely. This could have resulted in the demise of coral shallow communities turned to rubble by 2001. This could suit the trajectory of Scenario 6 discussed above, but only this one.

5.4.3. A kaleidoscope of processes difficult to reconcile

When searching for explanations, we thought we could quote the caveats from Hoeksma and Cleary (2004) when they argued with the interpretation by Abram et al. (2003) of the coral mortality in the Mentawai reef of west Sumatra: what we see on Bunaken satellite images is also likely “the result of a series of factors that produce outcomes that may be difficult to trace back to one single dominant cause and caution is required before oversimplifying things”.

A summary of the above discussion points out to COTS for possibly Scenario 4 and certainly for 5. Pre-2001 rapid sea level fall/storm/destructive fishing are suitable cause of coral loss for Scenario 6. No clear process can be identified for the fast loss seen for Scenario 4, except a possible combination of all factors (but without destructive fishing). Bleaching seems out of concern. Other stressors, like disease or pollution are difficult to include in the discussion without data. Identifying a different cause for each polygon is in fact not really satisfactory. While it is expected that disturbances can have patchy effects, such variety on a small domain is extreme.

Coral colonization occurred substantially with the same patchiness and just nearby the coral-loss area. Coral growth could be explained by sea level rise (Scenario 1, as in Scopelitis et al. 2011), and fast colonization by *Heliopora coerula*. The Figure 22 is an attempt to reconcile all these trajectories. The key hypothesis to propose a meaningful sequence of processes within short distances is the level of the reef floor relative to sea level. Slight topography differences of 10 cm could explain the sequence of mortality and growth that do not occur exactly on the same location at the same time. Initial conditions, pre-El Niño 1998, in Figure 22 are coral communities that have grown below the mean low water spring level (S3-6, S8), and sometimes close (Fig. 21). Areas S1-S3 are too close to sea level to allow coral growth. Then, rapid sea level fall in 1998 impacts only the shallowest communities on the crest (S6). After sea level return to normal, dead corals are left that slowly turned to rubble and get eroded. Remote sensing imaging start at that time in 2001. Sea level slowly rises in that period (Ampou et al. submitted) and previous areas S1-S3 benefit from new accommodation space where coral can recruit and grow, especially fast growing branching *Montipora* or *Heliopora*. Around Year 2007, COTS outbreaks impact area S5, and possibly area S4 if COTS feed on branching corals, but not in areas too shallow for COTS. *Porites* (S8) are not impacted by any of these events. Eventually, S4 and S5 have lost their corals, S1-S3 have gained corals, and S8 is stable. But it remains unclear why S3 or S4-S5 have not started to recover at some point at the level of changing the signal on the images. This level of recovery may still occur in the future since our 2015-2016 observations showed god level of recruitment in bare areas near the location of Scenario 4.

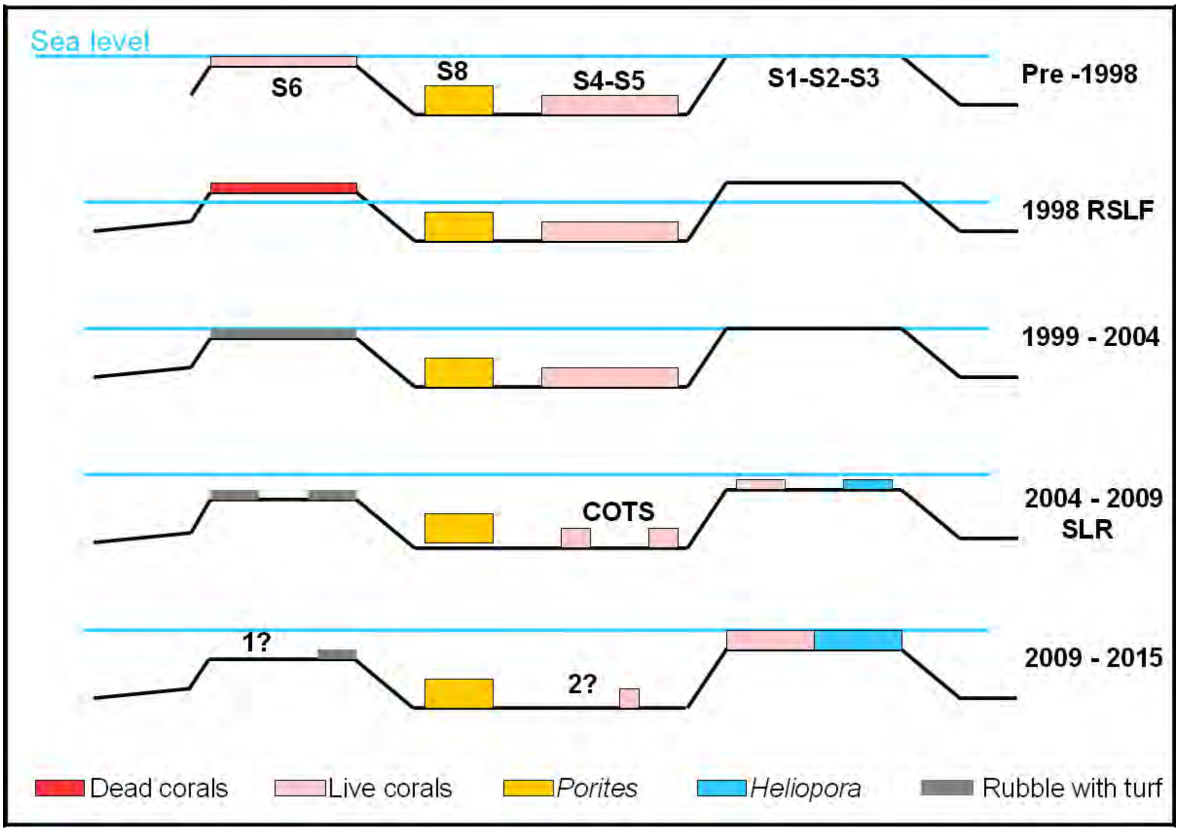

Figure 22: Suggested sequences of process and initial conditions to best reconcile the different scenarios, in chronological order from top-to-bottom and along an idealized transect crossing the different scenarios. The sand-seagrass scenario 7 is not shown here. RSLF: Rapid Sea Level Fall during the 1998 El Niño. SLR: Sea Level Rise after 1998. COTS: Crow of Thorn Starfish. S1-S8 refer to the scenario number. "?" summarizes the interrogation on why this area is not recolonized after the disturbance? See text for explanations on the sequence.

The temporal and spatial sequences in Figure 22 seem reasonable to reconcile the various scenarios and spatial patterns. However, to be validated, it is necessary to measure precisely the reef topography on relevant cross-reef sections. This information is not available. Single image processing to derive the bathymetry cannot offer the precision required (Hamylton et al., 2015). Stereo views could be suitable and need to be investigated (see Yamano, 2007), included with our images especially the couple of images acquired few days a part. A standard, non-image based, cross-reef topographic profile will also provide the answer. This survey is planned for the future, but data remains unavailable to date. In addition, vertical profiles within the live, or dead, branching carpet communities would help understanding more precisely their history, similar to what Piller and Riegl (2003) did for coral frameworks in Bali. These perspectives can be now pointed out after the remote sensing assessment is available and has identified critical gaps to fine-tune the understanding of coral community trajectories in Bunaken Island.

5.4.4. The influence of management and recommendations

Bunaken Island is a managed area. One can ask if management actions could explain the differences in trajectories of coral habitats. Similar question was raised by Newman et al. (2007), and they concluded it was not the case. No clear links existed between the types of uses in the zoning plan (described in 3 types of zones of decreasing level of protection: Core Zone, Tourism Use Zone, and General Use Zone) and the evolution of coral cover. The conclusion is the same for this study because different trajectories of coral gain or loss could occur on the same type of management area (General Use Zone and Tourism Use Zone). The Core Zone in the south part of the island appears as area of moderate changes, mostly due to seagrass bed variation, while the coral area towards the reef crest provides a trend similar to Scenario 8. Newman et al. (2007) suggested that the loss of coral cover they had quantified on a stretch of reef (called Lekuan/Liang) comprising Scenario 5 could be attributed to either divers or boat activities and the physical damage they would do to coral colonies. However, in 2014-2016, we stayed a total of ~8 weeks just in front of these areas, and considering the current practices, this hypothesis does not hold anymore. However, tramping and fishing with small nets may occur at low tide, but far less frequently than near the main village on the southeast tip of the island.

Bunaken Island and its fringing reef flats can be considered representative of many Indonesian reefs. Although it may remain specific in its biodiversity, local exposure to wave and wind, and tourism uses, the same dominant features and benthic zonations from shore to reef crests are widely found (Tomacsik et al., 1997). From this study, we support the conclusions by Scopélitis et al. (2010) that called for new adaptive approaches to monitor coral reefs combining remote sensing and field data to capture the diversity of changes at the scale of a reef. Often, typical monitoring may include only a handful of replicates for a reef, and we have again here the illustration that different locations can yield very different conclusions for the same reef, sometimes only few meters apart. Relying on only a couple of stations can be highly misleading to diagnose the status, and resilience, of an entire reef. Most biodiversity and coral monitoring programs may actually ignore coral reef flats, and focus on forereefs only (Turak and De Vantier, 2004; Kusen and Tioho, 2009). Same observation can be made for models (Mumby et al., 2006). We did not investigate here the walls and forereefs of Bunaken but we speculate that similar contrasting trajectories could be highlighted with field data, with deep habitats of increasing or decreasing quality around the island (Kusen and Tioho, 2009). For reef flats, remote sensing could be used to guide monitoring and adapt dynamically the location of sites to capture representative changes across the reef. From this particular study, we recommend a frequency of image acquisition every 2 years to avoid similar gap as in our archive between 2004 and 2009. Also, while we observed here almost exclusively "one-way" trajectories from one habitat to another, it is likely that oscillations could be observed on longer time series if they are maintained.

5.4.5. Methods for change detection beyond a scenario-based approach

Change detection is a vast remote sensing field that offers a wealth of methods that are continuously refined for new needs and new types of images (Lu et al., 2014; Falco et al., 2016). The main categories of processing according to Lu et al. (2004) include algebra-based approaches, transformation, classification, GIS method, visual interpretation, and other methods which can be hybrids, for instance knowledge-based approaches (Scopélitis et al., 2007). Each of these categories includes many different types of algorithms. Algebra-based methods for instance include image differences, ratios, index, regression or change vector analysis. In aquatic environments, not all methods are suitable, and thus far a handful of methods have been used (see Table 11). Bunaken Island has been the subject of change detection remote sensing studies by LeDrew et al. (2004) using SPOT images (20-meter resolution) and Newman and LeDrew (2007) using IKONOS images (4m). LeDrew et al. used a form of local indicator of spatial association (texture) to try to identify changes but the little reported variations are not discussed thematically. Newman and LeDrew estimated semi-quantitatively changes in coral cover by the differences of two supervised classifications. The results were discussed by management zone, but no detailed maps of change are provided.

By order of complexity, algebra-based and visual interpretation are the most simple methods. These are the methods we used here, based on several selection criteria: i) our goal was to identify representative scenario of changes and discuss Bunaken resilience, not mapping changes everywhere; ii) we had a multi-sensor time series, which count for additional challenges; iii) we thought that simple techniques are more likely to be adopted by managers and scientists that have little remote sensing expertise, or no access to it. Similar call for using simpler methods was previously made for coral reef habitat mapping (Andréfouët, 2008).

However, a minimum of pre-processing remains required to have co-registered and radiometrically consistent images that can be comparable across a time-series by difference or visual interpretation. The time series of images that was assembled by the INDESO project is unique and other algorithms will be tested in the future, in particular to fully map the changes. However, these algorithms, their results, and the interpretation of the results benefit now from the typology of changes draw here. Future automated and quantitative work can be thematically guided by the results presented here, including the type of habitat classes to focus on.

5.4.6. Bunaken, a resilient reef?

What can be concluded on the resilience of coral reef habitats in Bunaken Island? Do they appear resilient or not from this study? The different trajectories highlighted here describe a dynamic system with simultaneous degradation and recovery in a 15-year time frame. This time-window may be too short to definitely conclude on the long-term resilience capacities of Bunaken reefs. Palandro et al. (2008), Scopélitis et al. (2009) or Andréfouët et al. (2013) benefited for longer time series to highlight resilience through cycles of recovery and degradation of 15 years; or steady degradation. What is unambiguously demonstrated here is that Bunaken still presents the capacity to recover and regain coral cover and similar communities found 15 years ago (Scenarios 1-2), hence it has the attributes of a resilient reef, although not the entire reef has evolved in the same direction (Scenarios 4-6, 8). On the other hand, it seems that opportunistic species, like *Heliopora coerula*, may have conquered significant spaces (Scenario 3). How these new communities and the related strategy-shift can change the processes and functions of the reef warrant further investigation.

The trajectories of habitats in Figure 20 do not suggest any phase-shifts. The Scenarios 4-6 of coral loss end with bare substrate habitats, with lots of rubbles, but are not further evolving into habitats dominated by algae or soft corals, at least during our period of observations. Algae, or soft corals, do not seem to colonize these available substrates. Algae beds, during our 2014-2016 habitat surveys were present generally at the fringe of the eastern and western seagrass beds. They covered small areas. Fleshy brown and red algae (especially *Dictyota* sp., *Turbinaria* sp., *Acantophora* sp.), were always of small size, with a canopy less than 10 cm. Green algae were never abundant except *Halimeda* sppin seagrass beds. Cyanobacteria and turf algae were frequently found, but patchy. The abundant population of *Diadema* urchins may explain the lack of overgrowth by algae. *Diadema* form large conspicuous clusters on pavement and low density seagrass during the days, and are even visible on satellite images (Fig. 19).

5.5. Conclusion

One can object that resilience can not be assessed only with remote sensing images as we have tried to do here. Other small scale (e.g., recruitment, trophic chain) and/or large-scale (e.g., connectivity) processes must be studied. We agree that these processes are important to address the mechanics of resilience, but our observations here have integrated the action of these processes for the studied period and the integrated outcome was quantified using remote sensing. We conclude that Bunaken Island reef flats have demonstrated a capacity to regain coral cover, but not necessarily everywhere. We highlighted a 8-scenario typology of habitat trajectories, but we agree that the mechanisms behind these trajectories remain incompletely understood. Further research, additional data collection, and integrated study combining remote sensing, field work and spatial modelling are needed to refine the understanding on how Bunaken coral reefs work. Bunaken Island, and the National Park around, has been one of the flagship for Indonesian coral reef research nearly two decades ago, and we suggest this status should be maintained on the long run to become a pilot-site in the study of the resilience of Indonesian coral reefs.

CHAPTER 6. DISCUSSION, PERSPECTIVES AND RECOMMENDATION

The previous chapters have presented original results and approaches to study the reefs of Bunaken Island using remote sensing. We review here the main results and lessons for each chapter, and discuss potential perspectives for the study of Bunaken, but also, for other Indonesian reefs in general.

In Chapter 3, we investigated if we could represent the high richness of the habitats present around Bunaken by adapting a habitat mapping protocol based on photo-interpretation. We provided a typology of 175 habitats identified in the field, on 6 geomorphological strata, in 2014 and 2015 (see Appendices 1 and 2). These 175 habitats were not redundant based on cover data, but they cannot be all recognized by photo-interpretation on a Geoeye-1 image acquired in 2014. Thus, to keep all the thematic information in a map, we endeavoured to craft a habitat map for which each polygon is documented by the list of habitats that can be found on the area of the polygon (Appendix 3). The result is a thematically rich product, probably the richest ever made in the field of coral reef habitat mapping, but its use poses a number of problems. In particular, documenting the accuracy of such map is also a challenge, since a confusion matrix is in fact needed for each polygon to understand how accurate it is. While the resulting map and attribute table include all the thematic information, the product can be overwhelming for a user not familiar with all reef habitats. This is also why we provided an ID card for each of the identified habitat (Appendix 2), in the hope that people interested by habitat maps can become more aware of the richness of the configurations found in Indonesia. However, we conclude that providing a very high thematic resolution product remains a challenge if we expect that the products become part of the routine work of managers and scientists. Significant compromises and simplification remain needed with multispectral images, even at very high spatial resolution, and in further work, we will degrade our original product into a more traditional product, with one habitat defined for each polygon. Unfortunately, the consequence is that typical habitat maps that are manageable by non-specialist users can not really make justice to the richness of an Indonesian site.

The benefit of creating a "hyperdetailed" map is that the complexity of the Bunaken reefs and its tight mosaic has been assessed, and we could get very familiar with the various locations, noticing changes, or not, that may have occurred between field trips. Potentially, each habitat is the consequences of a variety of processes that result in what each habitat looked like in 2014-2015 at the time of our visit. Disturbances, recruitment, mortality, growth, erosion, and competition between the main habitat components, have all necessarily combined differently on each polygon that we have mapped. We recognize that functional redundancy is certainly present among our habitat typology, but we also believe that each habitat point to a specific combination of processes, and equilibrium, which are therefore very high on the small area covered by Bunaken reefs. Otherwise, if the complexity of processes were low, many more habitats would be similar. We had the opportunity to demonstrate this paradigm by witnessing in 2016 the effects of the 2015-2016 El Niño on a limited numbers of reef habitats, due to sea level fall. We documented In Chapter 4 the impacts of this event which took the form of coral mortality on the upper part of colonies. We estimated that sea level anomalies in September 2015 resulted in up to 80% mortality for coral habitats characterized by communities living close to the lower mean sea level. This illustrates how specific processes can be around Bunaken, even in the case of the strongest El Niño on records. Yet, we suspect that many Indonesian shallow reefs have vastly suffered from a similar process. Furthermore, the impact has preceded the bleaching event that followed between April-June 2016, due to thermal stress. While Bunaken was not concerned by the 2016 bleaching, others reefs have been, especially on the Indian Ocean side of the country. Our study points out to the need to include information on sea level when designing monitoring programs in Indonesia, and when analysing data on shallow reefs.

Coral mortality due to unusual low water levels was not a discovery at all, but the Chapter 4 pointed to a threat never really described for Indonesian reef flat communities. Importantly, the event that we witnessed pointed to an important process that certainly plays a significant role in the resilience of Bunaken reefs. Without real-time observations, we could have neglected the role of occasional sea level fall in shaping up Bunaken reefs. The initial goal of this thesis was to assess the value of using very high spatial resolution images to monitor coral reefs in Indonesia. In particular for Bunaken, we wanted to assess if the reefs have changed at some point, and if the reefs were resilient or not. In Chapter 5, we demonstrate this potential by using a unique multi-sensor time-series of VHR images from 2001 to 2015. Using simple change detection analysis techniques, we show that Bunaken reef flats have been highly dynamic in the past 15 years. We highlighted a variety of habitat trajectories, sometimes in complete opposite direction, that have occurred on reef flats. The biggest challenge was to explain the different trajectories found sometimes on very close proximity, and identify a suite of processes that could fit the observations. Despite being one of the most studied sites in Indonesia, in fact; Bunaken quantitative georeferenced data are scarce and ancillary data that could have helped us interpreting changes visible on images were non-existent. However, several useful papers were available, including the description of a *Acanthaster planci* outbreak in 2007 (Tokeshi & Daud, 2011). But except information on sea level and this *A. planci* episode, we used general knowledge and common-sense to reconcile the different trajectories that we observed. We found that is it possible to explain our image-based observations, however, we had to draw hypothesis on the topography of the reef, which is a key player during sea level variations. Unfortunately, we became fully aware of the role of sea level only late in this thesis, and we could not add another field trip in 2016 to measure the reef topography around the island, using simple in situ survey techniques. This can be achieved later, as a perspective to validate our model of reef evolution that takes into account the type of reef communities, the reef topography, the effect of sea level variations, and predation/mortality episodes by *A. planci*.

Overall, this thesis has provided new important thematic results on Indonesian coral reefs. First, this thesis contributes to enhance our knowledge of the richness of Indonesian reef habitats. It provides a first detailed habitat typology, and associated habitat maps, and hence contributes to enhance our knowledge of Indonesian marine biodiversity. Second, we identified an important process that controls shallow reef resilience, namely sea level fall. This process is not specific to Indonesia of course, and is likely variable within Indonesia, but its importance is proven, at least for Bunaken. It also reminds us that bleaching is not the only cause of mortality during El Niño episodes. Finally, we have shown that remote sensing bring evidences of changes occurring on reefs. Monitoring shallow reef flats can thus be achieved for Indonesian reefs, within some limits. This was already demonstrated for other parts of the world, but the limits of thematic interpretation are also shown here for Indonesia. However, based on our results that display a mixed bag of representative and diametrically opposite trajectories in terms of coral cover evolution, it is difficult to conclude on the resilience of Bunaken reefs using VHR images only. At the time-scale we could complete this study, we conclude however that Bunaken is not experiencing any phase-shifts, from coral dominance to algae dominance. Bunaken displays without ambiguity the capacities to increase coral cover, and several of the habitats of the typology are also displaying good level of recruitment for a variety of communities.

We conclude this thesis by emphasizing the high biodiversity of Indonesia marine waters, here demonstrated at the habitat level for the first time using a combined field and remote sensing approach. We hope that new sites investigated in a similar way will continue to enhance this knowledge. The INDESO project has already several sites added but we can only hope for more. Second, we would like to emphasize the value of continuous work on Bunaken Island, and Bunaken National Park in general. This is a fascinating area. It has been an icon of research on Indonesian coral reefs about twenty-fifteen years ago and we hope that it will be maintained at the same level in the future, with continuous future work. Bunaken offers many interesting areas to develop new field and remote sensing research. In particular, the Bunaken VHR image time-series could be maintained, and the analysis of the time series could be the object of various methodological projects in image processing. Finally, as a general recommendation, we suggest that in the future, despite the substantial cost of acquiring and processing VHR remote sensing images for a country like Indonesia, this tool becomes more and more part of the toolbox of indonesian scientists working on coral reefs in Indonesia. The spatial information, and its richness, is unvaluable to guide on-going and future science and management projects of Indonesian reefs. However, not all science and management projects need VHR images. Many challenges can be overcome with lower resolution and free images. Identifying the exact processing strategy requires experience, and we believe Indonesia will benefit from the expertise learned during this PhD. Sekarang, selamat bekerja Elvan !!!!

CONCLUSION (in French)

L'objectif principal de la thèse était de déterminer si les habitats des récifs coralliens dans l'île de Bunaken (IB) dans le nord de Sulawesi sont résilients, en utilisant i) des cartes d'habitat nouvellement conçues, ii) des données in situ et une série chronologique de 15 ans unique d'images satellites de différents capteurs à très haute résolution (VHR), iii) des données auxiliaires qui pourraient expliquer les changements détectés. En effet, la compréhension de la résilience des habitats du récif corallien est considérée comme une priorité, en particulier pour percevoir les effets des mesures de gestion et de stress.

La thèse présente les résultats obtenus sous la forme de 3 grands chapitres, chacun correspondant à une publication distincte.

Tout d'abord, une carte extrêmement détaillée de l'habitat des récifs autour de IB a été créée en utilisant une image GeoEye-1 de résolution 2m et des données de vérité-terrain recueillies en 2014-2015 (Chapitre 3, publication soumise à *Marine Pollution Bulletin*). L'objectif était de créer une carte qui rende compte de la complexité et de la richesse des habitats trouvés autour de la petite île de Bunaken (5 km^2 de récifs). Une carte d'habitats de 194 polygones a été créée par photo-interprétation, en utilisant des méthodes et des boîtes à outils simples disponibles dans le logiciel ENVI. Chaque polygone a reçu une liste d'habitats possibles établis parmi une liste de 175 habitats identifiés dans 6 zones géomorphologiques (tombant, pente, crête, platier, terrasse et lagon) (Annexe 1). Le produit et les informations (liste des habitats par polygone) peuvent être évalués en utilisant des données de contrôle de vérité-terrain. Ces observations aboutissent à une matrice d'erreur pour chaque polygone en fonction des différences de présence / absence entre les habitats cartographiés et les observations de l'habitat in situ (Annexe 3). Le résultat est un produit thématiquement riche, sans doute le plus riche jamais obtenu dans le domaine de la cartographie des habitats des récifs coralliens, mais son utilisation pose un certain nombre de problèmes. En particulier, documenter l'exactitude de cette carte est aussi un défi, car une matrice de confusion est en effet nécessaire pour comprendre la précision obtenue sur chaque polygone (Annexe 4). Bien que la carte et la table résultante comprennent toutes les informations thématiques, le produit peut être compliqué pour un utilisateur ne connaissent pas tous les habitats récifaux. C'est également la raison pour laquelle nous avons fourni une carte d'identité pour chacun des habitats identifiés (Annexe 2), dans l'espoir que les gens intéressés par les cartes d'habitats puissent devenir plus conscients de la richesse des configurations trouvés en Indonésie. Cependant, nous concluons que la fourniture d'un produit de résolution thématique très élevé reste un défi si nous visons une utilisation de routine de ces produits par des gestionnaires et des scientifiques. Des compromis et simplification significatifs restent nécessaires avec des images multispectrales, même à très haute résolution, et dans le futur, nous dégraderons notre produit d'origine dans un produit plus usuel, avec un habitat défini pour chaque polygone. Il en résultera cependant que les cartes d'habitats typiques gérables par les utilisateurs non-spécialistes ne pourront pas vraiment rendre compte de la richesse d'un site indonésien.

Deuxièmement, nous avons observé la mortalité du corail en Mars 2016, et documenté l'événement pour plusieurs des habitats identifiés ci-dessus. En Septembre 2015, les données d'altimétrie montrent que la mer était à son niveau le plus bas au cours des 12 dernières années en raison du très fort événement El Niño, ce qui affecte les coraux les moins profonds. En Mars 2016, IB affiche une mortalité jusqu'à 85% sur les platiers où dominent les coraux *Porites*, *Heliopora* et *Goniastrea* avec des taux de mortalité dépendant du genre. Presque tous les platiers récifaux ont connu une mortalité, ce qui représente 30% des récifs de l'île de Bunaken. Les données altimétriques ont été utilisées pour cartographier la baisse du niveau de la mer sur toute l'Indonésie, ce qui suggère qu'une mortalité similaire a pu se produire sur d'autres récifs indonésiens peu profonds. Les données historiques altimétriques suggèrent également que cet événement n'a pas été unique au cours des deux dernières décennies, et donc que la chute rapide du niveau de la mer pourrait être plus importante dans la dynamique et la résilience des récifs indonésiens qu'on ne le pensait. L'ensemble de ces résultats, détaillés dans le Chapitre 4, reprennent une publication soumise à *Biogeosciences*, en cours d'évaluation (http://www.biogeosciences-discuss.net/bg-2016-375/).

Enfin, les séries chronologiques de l'imagerie satellitaire VHR ont été utilisées pour caractériser la dynamique à long terme des habitats de l'île de Bunaken, en particulier sur les platiers peu profonds, entre 2001 et 2015 (Chapitre 5, publication soumise à *Marine Pollution Bulletin*). Le manque de données de terrain historiques géoréférencées nous a conduits vers une approche de scénarios basée sur le suivi d'une sélection de polygones d'habitat évoluant sans ambiguïté et caractérisés in situ en 2014 et 2015. Cela a permis d'identifier des scénarios représentatifs des changements et de discuter de la résilience de Bunaken. Étonnamment, les trajectoires de patchs de corail étaient très différentes, y compris sur de petites zones. Des communautés de corail dominées par différents coraux ont pu apparaître stables, disparaître complètement, brusquement ou lentement, ou coloniser lentement ou rapidement de nouveaux substrats. En parallèle, les herbiers à proximité se sont en général développés en taille et en densité dans la période étudiée. Ces scénarios qui se sont produits simultanément ont été identifiés dans des zones proches, ce qui empêche l'identification d'une seule cause générale des changements qui pourraient avoir une incidence sur l'ensemble du récif. Probablement, les différences subtiles de topographie, de l'exposition au vent / vagues et de variation du niveau de la mer sont responsables de la variété des résultats.

Dans l'ensemble, cette thèse a fourni de nouveaux résultats thématiques importants sur les récifs coralliens indonésiens. Tout d'abord, elle contribue à améliorer notre connaissance de la richesse des habitats des récifs indonésiens. Elle fournit une première typologie détaillée des habitats, et des cartes d'habitats associées, et donc contribue à améliorer notre connaissance de la biodiversité marine indonésienne. Deuxièmement, nous avons identifié un processus important qui contrôle la résilience des récifs peu profonds, à savoir la baisse du niveau de la mer, à l'occasion des événements El Niño. Ce processus n'est pas spécifique à l'Indonésie bien sûr, et il est probablement variable en Indonésie, mais son importance est prouvée, au moins pour Bunaken. Ce résultat nous rappelle également que le blanchissement n'est pas la seule cause de mortalité des coraux durant les épisodes El Niño. Enfin, nous avons montré que la télédétection peut apporter des preuves de changements qui se produisent sur les récifs. La surveillance des platiers peu profonds peut ainsi être poursuivie sur les récifs indonésiens, dans certaines limites. Cela a déjà été démontré sur d'autres parties du monde, mais les limites de l'interprétation thématique sont également présentées ici pour l'Indonésie. Cependant, sur la base de nos résultats qui affichent un mélange de trajectoires représentatives et diamétralement opposées en termes d'évolution de la couverture corallienne, il est difficile de conclure sur la résilience des récifs Bunaken en utilisant uniquement des images THR. Nous avons conclu que IB démontre une capacité de résilience et n'a pas connu de déphasage, mais qu'un diagnostic définitif de la résilience de l'île de Bunaken reste difficile à déterminer par la seule imagerie. La cartographie précise sur Bunaken montre qu'un récif particulier peut être un kaléidoscope de comportements très différents. Ces trajectoires ne peuvent pas être totalement détaillées sans changer certains paradigmes de surveillance. Une combinaison d'observations de télédétection (VHR pour les récifs eux-mêmes et d'autres données autour des récifs) et de données in situ reste la meilleure stratégie pour mieux comprendre la dynamique des récifs coralliens indonésiens.

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APPENDIX I

HABITAT LIST IN-SITU TYPOLOGY

REEF CREST

					CORAL													OTHER							SPONGE										
IDF	ID-Geom	GEOMORPHOLOGY		RUGOSITY	CBr	Cmas	Cenc	Cfol	Cmush	Cssubm	Millep	Heliop	ABR	ACT	ACD	SoftC	DeadC	Sg	Alg	Turf	BlackCor	SU	Gorg	Hyd	BaS	EnS	brS	FoS	MS	RCK	BLD	RUB	PAV	SAND	TOTAL (%)
1	6	Crest	coral	3	2	25	2			2	2					2																5	60		100
2	7a	Crest	coral	4	40	5	5			5						5														20		10	10		100
3	7b	Crest	coral	4	10	10	10			2			5	20																28			15		100
4	7c	Crest	coral	4	10	30	20							2																20			18		100
5	8	Crest	coral	4	6	6	6			2				5		30														15	10	10	10		100
6	10	Crest	coral	4	15	15	5			10				10		25														20					100
7	11	Crest	coral	4	10										85	5																			100
8	12	Crest	coral	4		5							85			5														5					100
9	13	Crest	coral	3	5										50	40														5					100
10	14	Crest	coral	4	40	10							15	20																10		5			100
11	15	Crest	coral	4	80	2	2	1		2						2								1						10					100
12	16	Crest	coral	4	25	5	5	5		5			30		14	1														10					100
13	17	Crest	coral	4	25	5	5			5			15	40																5					100
14	18	Crest	coral	4	20	20	3			10				40		2														5					100
15	19	Crest	coral	4	10	50	5			5			5			5								5	1			2	2	10					100
16	20	Crest	coral	3	50	2	2			2			2			2														10		5	25		100
17	21	Crest	coral	4	40	15	5			15			5			10														10					100
18	22	Crest	coral	4	20	5	5	15		10			20	5		10								5						5					100
19	23	Crest	coral	4	45	30																			10								15		100
20	24	Crest	coral	4	15	10	10	5		10			10	5		10								15	2	1		1	1	5					100
21	25	Crest	coral	4	5	20	5			5			5			10								30	1	1		1	1	16					100
22	26	Crest	coral	4	25	10	5			2						1														7	20	30			100
23	5	Crest	coral	4	20	5	2			2						5														20			46		100
24	1	Crest	rubble	3	1											1															38		50	10	100
25	2	Crest	rubble	3																											100				100
26	3	Crest	rubble	2																												100			100
27	3b	Crest	soft	2												70														5		25			100
28	3c	Crest	soft	3	2	2										70								5						6		10		5	100
29	3d	Crest	soft	3	5	2										50								23								20			100
30	9	Crest	soft	3	2	1	1			1						70														25					100
31	4	Crest	pavement	3	1	1	15			1						1				2						4							75		100

LAGOON

IDF	ID-Geom	GEOMORPHOLOGY		RUGOSITY	CORAL													OTHER							SPONGE										
					CBr	Cmas	Cenc	Cfol	Cmush	Cssubm	Millep	Heliop	ABR	ACT	ACD	SoftC	DeadC	Sg	Alg	Turf	BlackCor	SU	Gorg	Hyd	BaS	EnS	brS	FoS	MS	RCK	BLD	RUB	PAV	SAND	TOTAL (%)
32	2	Lagoon	coral	3							5		60																			20		15	100
33	3	Lagoon	coral	3	30								30																			30		10	100
34	4	Lagoon	coral	3	90																											5		5	100
35	5	Lagoon	coral	4		40							20																	25		10		5	100
36	1	Lagoon	seagrass	1														10														10		80	100
37	6	Lagoon	sponge	2		5											5	5	5								40					30		10	100

REEF FLAT 1

IDF	ID-Geom	GEOMORPHOLOGY		RUGOSITY	CORAL											SoftC	DeadC	OTHER							SPONGE					RCK	BLD	RUB	PAV	SAND	TOTAL (%)
					Cbr	Cmas	Cenc	Cfol	Cmush	Csubm	Millep	Heliop	ABR	ACT	ACD			Sg	Alg	Turf	Black Cor	SU	Gorg	Hyd	BuS	EnS	IncS	EoS	MS						
38	46	Reef flat	algae	2														5	85														10		100
39	47	Reef flat	algae	2														20	60													10	10		100
40	52	Reef flat	algae	2		10													80											5	5				100
41	54	Reef flat	algae	2	5														40													55			100
42	7	Reef flat	coral	3		25	2			5			2			1													2			10	49	4	100
43	8	Reef flat	coral	2		25				2			1																2				65	5	100
44	9	Reef flat	coral	3		30																										20	30	20	100
45	9b	Reef flat	coral	3		10	5					20	1																			5	59		100
46	10	Reef flat	coral	3		10							30																				60		100
47	10b	Reef flat	coral	3	30	5																										15	50		100
48	14	Reef flat	coral	2		20						2				5			8													65			100
49	16a	Reef flat	coral	2		20	20																									60			100
50	16b	Reef flat	coral	3	30		40												5											15		10			100
51	16c	Reef flat	coral	2	10	10	20					10							5													45			100
52	16d	Reef flat	coral	3	10	15	15						10																			5	40	5	100
53	17	Reef flat	coral	3		40																								10		50			100
54	18	Reef flat	coral	3	15	5																						1		10	20		20	29	100
55	19	Reef flat	coral	3	5	5	10					5				5															10	40	20		100
56	21	Reef flat	coral	3		20			1			20				10														10		39			100
57	22	Reef flat	coral	4		30	5							10																20		5	30		100
58	23	Reef flat	coral	3		25	2			5			2			10													2			10	40	4	100
59	24	Reef flat	coral	3		50											20															10		20	100
60	25	Reef flat	coral	3	20	50										10																20			100
61	26	Reef flat	coral	3		10											50																	40	100
62	30	Reef flat	coral	3	10	45	10																							10			25		100
63	31	Reef flat	coral	2	10	10	20					2				10			5											13			30		100
64	32	Reef flat	coral	3		20						5																			75				100
65	32b	Reef flat	coral	3	2	60	2			2		2																		17				15	100
66	33	Reef flat	coral	3	15	56	2			2		10				5														10					100
67	36	Reef flat	coral	3	5	5						60					30																		100
68	38	Reef flat	coral	3	75	5											20																		100
69	40	Reef flat	coral	3	80			10									5																	5	100
70	42	Reef flat	coral	4	95			5																											100

REEF FLAT 2

IDF	ID-Geom	GEOMORPHOLOGY		RUGOSITY	CORAL											SoftC	DeadC	OTHER							SPONGE					RCK	BLD	RUB	PAV	SAND	TOTAL (%)
					CBr	Cmas	Cenc	CFol	Cmush	Csubm	Millep	Heliop	ABR	ACT	ACD			Sg	Alg	Turf	Black Cor	SD	Gorg	Hyd	BaS	EnS	brS	PoS	MS						
71	43	Reef flat	coral	4	60	3	2	2		2				20		5												2						5	101
72	44	Reef flat	coral	3	60												20		15													5			100
73	45	Reef flat	coral	4									70				5	5														10		10	100
74	49	Reef flat	coral	3	80													20																	100
75	9c	Reef flat	deadcoral	3								20					50															30			100
76	34	Reef flat	deadcoral	3	10	5						5					55													10	5	10			100
77	35	Reef flat	deadcoral	3		5											80													5	10				100
78	37	Reef flat	deadcoral	3		5						5					75		15																100
79	41	Reef flat	deadcoral	2	5	1										5	89																		100
80	1	Reef flat	pavement	1																													90	10	100
81	2	Reef flat	pavement	1																													70	30	100
82	3	Reef flat	pavement	1		1	1																				2				6		90		100
83	4	Reef flat	pavement	2		1																									40	9	50		100
84	5	Reef flat	pavement	2		10																											85	5	100
85	6	Reef flat	pavement	3		10	5						5																		1	5	65	9	100
86	29	Reef flat	pavement	2		15	9		1							30																	45		100
87	53	Reef flat	pavement	2	10														30														60		100
88	11	Reef flat	rubble	2		5							5																	5		60	25		100
89	12	Reef flat	rubble	3																											80	20			100
90	13	Reef flat	rubble	2		10										5			20													65			100
91	20	Reef flat	rubble	3	10	5																								50		35			100
92	51	Reef flat	rubble	1														30	20													50			100
93	48	Reef flat	seagrass	1														90													10				100
94	50	Reef flat	seagrass-coral	3	50													50																	100
95	27b	Reef flat	soft	4		5										75														10				10	100
96	28	Reef flat	soft	3		5										70																	20	5	100
97	39	Reef flat	soft	2	30	5										55	10																		100
98	27	Reef flat	soft-coral	4		15										50	5													10				20	100

SLOPE

IDF	ID-Geom	GEOMORPHOLOGY		RUGOSITY	CORAL											SoftC	DeadC	OTHER							SPONGE					RCK	BLD	RUB	PAV	SAND	TOTAL (%)
					CBr	Cmas	Cenc	Cfol	Cmush	Csub	Mille	Helio	ABR	ACT	ACD			Sg	Alg	Turf	Black Cor	SU	Gorg	Hyd	BaS	EnS	brS	EoS	MS						
99	3	Slope	coral	3	5	5	5																							10		30		45	100
100	4	Slope	coral	4	5	5	5										20													40				25	100
101	7	Slope	coral	4	10	3	6	6	5	2	1					10							2		10					20		15		10	100
102	8	Slope	coral	4	20	1	1																							30	30	10		8	100
103	9	Slope	coral	4	15	10				3						30								2						10	5	15		10	100
104	10	Slope	coral	3	30	30																										15	25		100
105	11	Slope	coral	4	20	5	5			5					5	5									20		5			5		10		15	100
106	12	Slope	coral	4	25	5		5	1	15																				20		27		2	100
107	13	Slope	coral	4	25	15	5	10		5					10										20					10					100
108	14	Slope	coral	4				35									15								20		5		5	10		5		5	100
109	15	Slope	coral	4	10	5		20					60																	5					100
110	16	Slope	coral	4				85					5												10										100
111	18	Slope	coral	4	30	10	5	40																	10					5					100
112	19	Slope	coral	4	10	5		30									40								10					5					100
113	20	Slope	coral	4	95																									5					100
114	21	Slope	coral	4	2	45				2											1					20				30					100
115	22	Slope	coral	4	5	25	5			5						25								15	15	5									100
116	23	Slope	coral	4	30	15		20																						20				15	100
117	24	Slope	coral	2		5	20														5				5			5		60					100
118	25	Slope	coral	3	5	5	5			5						15								5						20		5	30	5	100
119	26	Slope	coral	4	5	36	5	5		2					2																15	5		25	100
120	17	Slope	deadcoral	4				15									85																		100
121	5	Slope	rubble	2																												80		20	100
122	6	Slope	rubble	3	2	2				2																	5			9		55		25	100
123	6b	Slope	rubble	3	10	2																		15						8		55		10	100
124	27	Slope	rubble	1		5																											95		100
125	1	Slope	sand	3	1																			1						10				88	100
126	2	Slope	sand	3	5	5							10																			5		75	100

TERRACE

IDF	ID-Geom	GEOMORPHOLOGY		RUGOSITY	CORAL											SoftC	DeadC	OTHER							SPONGE					RCK	BLD	RUB	PAV	SAND	TOTAL (%)
					Cbr	Cmas	Cenc	Cfol	Cmush	Csubm	Millep	Heliop	ABR	ACT	ACD			Sg	Alg	Turf	BlackCor	SU	Gorg	Hyd	BaS	EnS	IncS	RoS	MS						
127	10d	Terrace	algae	2														15	75													15		5	110
128	14	Terrace	algae	1																30													50	20	100
129	15	Terrace	algae	2														5	60													15	15	5	100
130	16	Terrace	algae	2														5	45													40	10		100
131	17	Terrace	algae	2														1	80													14		5	100
132	10a	Terrace	algae-seagrass	2														75	25																100
133	10b	Terrace	algae-seagrass	2														85	15																100
134	10c	Terrace	algae-seagrass	2		1												64	15													10		10	100
135	10e	Terrace	algae-seagrass	2														60	30															10	100
136	11f	Terrace	coral	2		60											20	20																	100
137	11e	Terrace	deadcoral	2													60	20												10		10			100
138	19	Terrace	mix	2															5									5		35				55	100
139	4	Terrace	pavement	1															5													5	20	70	100
140	18	Terrace	pavement	1		1													20									5				2	70	2	100
141	12b	Terrace	rubble	2														25														75			100
142	13a	Terrace	rubble	1														5														95			100
143	13b	Terrace	rubble	2		10											5	5														80			100
144	1	Terrace	sand	1																														100	100
145	2	Terrace	sand	1														1																99	100
146	5	Terrace	sand	1															5													15		80	100
147	6b	Terrace	sand	1														15																85	100
148	3	Terrace	seagrass	2														40																60	100
149	6a	Terrace	seagrass	1														30																70	100
150	6c	Terrace	seagrass	1														70														15		15	100
151	6d	Terrace	seagrass	2														15														10	35	40	100
152	7a	Terrace	seagrass	2														50																50	100
153	7b	Terrace	seagrass	2														70																30	100
154	7c	Terrace	seagrass	2														60																40	100
155	7d	Terrace	seagrass	2		10												60														10		20	100
156	7e	Terrace	seagrass	2														50	10										15					25	100
157	8a	Terrace	seagrass	2														80																20	100
158	8b	Terrace	seagrass	2														80												20					100
159	8c	Terrace	seagrass	2														80																20	100
160	9	Terrace	seagrass	2														99																1	100
161	11a	Terrace	seagrass	3	30													45				5								5		15			100
162	11b	Terrace	seagrass	2												20		60														20			100
163	11c	Terrace	seagrass	2								15						65												20					100
164	11d	Terrace	seagrass	2	50													40														10			100
165	12c	Terrace	seagrass	2														75														25			100
166	12a	Terrace	seagrass-rub	2														25														70		5	100

WALL

IDF	ID-Geom	GEOMORPHOLOGY		RUGOSITY	CORAL											SoftC	DeadC	OTHER							SPONGE					RCK	BLD	RUB	PAV	SAND	TOTAL (%)
					CBr	Cmas	Cenc	CFol	Cmush	Csubm	Millep	Helipo	ABR	ACT	ACD			Sg	Alg	Turf	BlackCor	SU	Gorg	Hyd	BaS	EnS	brS	FoS	MS						
167	4	Wall	coral	4	10	20	20	10		2						2			7		1		1		1	10	1		5	10					100
168	5	Wall	coral	4		20		60											5											15					100
169	7	Wall	coral	4	5	20	5	10		2							4		5		10		1		2	2	2		2	20		10			100
170	8	Wall	coral	4	20	22	5			2									5		5		1	3	3	3	3		3		25				100
171	9	Wall	coral	4	4	10	5	10		2						1			5						1	15	2	5		40					100
172	1	Wall	mix	4	2		2			2			1			5			7		20		5		1	5	5		5	40					100
173	2	Wall	mix	4	2		2	10		2			2	2		5			7				20		1	5	5		5	32					100
174	6	Wall	mix	4	5	10	9	5		2						5					1		1	1	5	2	2		2	30		20			100
175	3	Wall	sponge	4	5	5	5	10		2									7		1		1		10	14	10		10	20					100

APPENDIX II

HABITAT ID CARD

HABITAT 1

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Massive forms < 25%
Porites, Goniastrea, Hydnopora, Isopora, Millepora

Zoanthids

Substrate:
Pavement, rubble

Rugosity: 3

HABITAT 2

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S13-2014

Hard Coral:
Porites cylindrica dominant, *mix* > 40%

Soft coral present

Substrate:
Rock, pavement, rubble

Rugosity: 4

HABITAT 3

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Acropora tables, *Porites, Montipora, etc.* > 50%

Substrate:
Rock, pavement

Rugosity: 4

HABITAT 4

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014

Hard Coral:
Mix with dominant encrusting and massive forms > 25%

Zoanthids

Substrate:
Rock, pavement

Rugosity: 4

HABITAT 5

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Mix < 20%

Soft coral:
Sinularia > 10%

Substrate:
Rock, boulder, rubble

Rugosity: 4

HABITAT 6

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S14-2014

Hard Coral:
Mix incl. *Porites, Isopora, Acropora* tables >60%

Soft coral:
Sinularia >15%

Substrate:
Rock

Rugosity: 4

HABITAT 7

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Raymonds point

Hard Coral:
Acropora, Isopora
>80%

Soft coral: present

Rugosity: 3

HABITAT 8

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Acropora
branching
dominant >80%

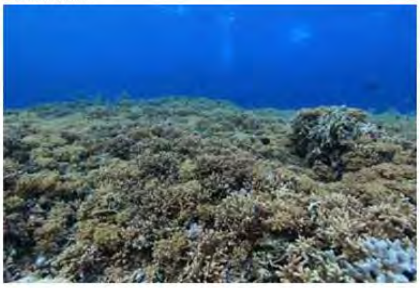
Rugosity: 4

HABITAT 9

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Sachico



Hard Coral:
Acropora
branching >50%

Soft coral:
Sinularia >30%

Substrate:
Rock

Rugosity: 3

HABITAT 10

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Mix, *Acropora, Goniastrea, Porites cylindrica*
>80%

Substrate:
Rock, rubble

Rugosity: 4

HABITAT 11

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S18-2014

Hard Coral:
Porites cylindrica
>60%

Soft coral, hydroids present

Substrate:
Rock

Rugosity: 4

HABITAT 12

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S18-2014

Hard Coral:
Mix growth forms branching, encrusting, foliose, sub-massive >80%

Substrate:
Rock

Rugosity: 4

HABITAT 13

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Mix dominated by large *Acropora* tables, *Porites cylindrica* >80%

Substrate:
Rock

Rugosity: 4

HABITAT 14

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S10-2014

Hard Coral:
Mix with large *Acropora* tables, >80%

Substrate:
Rock

Rugosity: 4

HABITAT 15

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S5-2014

Hard Coral:
Dominated by Porites lutea, mix > 50%

Soft coral <10%

Hydroids <10%

Substrate:
Rock

Rugosity: 4

HABITAT 16

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014

Hard Coral:
Dominated by *Isopora* >40%

Substrate:
Rock, pavement, rubble

Rugosity: 3

HABITAT 17

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S10-2014

Hard Coral:
Mix dominated by Isopora > 80%

Substrate:
Rock

Rugosity: 4

HABITAT 18

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: D4-2015

Hard Coral:
Mix of all growth forms, incl. *Echinopora, Acropora, Porites,* etc. >80%

Soft coral:
Sinularia <10%

Hydroids present

Substrate:
Rock

Rugosity: 4

HABITAT 19

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: D2-2015

Hard Coral:
Mix with presence of *Tubastrea* >20%

Sponge:
Xestospongia

Substrate:
Rock

Rugosity: 4

HABITAT 20

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Raymond's point

Hard Coral:
Mix >50%

Soft coral:
Sinularia >10%

Hydroids (*Aglaophenia*)>10%

Sponges present

Substrate:
Rock

Rugosity: 4

HABITAT 21

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Sachiko

Hard Coral:
Mix <30%

Soft coral:
Sinularia >10%

Hydroids (*Aglaophenia*)>10%

Sponges present

Substrate:
Rock

Rugosity: 4

HABITAT 22

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Pangalisang

Hard Coral:
Mix <30%

Substrate:
Large boulder, rubble, rock

Rugosity: 4

HABITAT 23

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard coral:
Porites cylindrica, mix >15%

Soft coral:
<5%

Substrate:
Pavement, rock

Rugosity: 4

HABITAT 24

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S13-2014

Hard Coral:
Present

Substrate:
Large boulder, pavement, sand

Rugosity: 3

HABITAT 25

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Substrate:
Large boulder

Rugosity: 3

HABITAT 26

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Sachico

Substrate:
Rubble

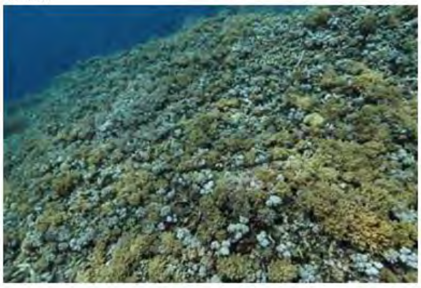
Rugosity: 2

HABITAT 27

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:



Soft coral:
Sinularia, Nephtea > 60%

Substrate:
Rubble, rock

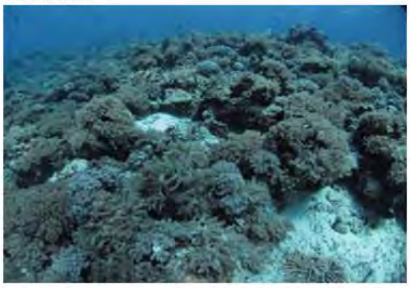
Rugosity: 2

HABITAT 28

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Sachico



Soft coral:
Sinularia >50%

Hard coral:
<5%

Substrate:
Rubble, sand

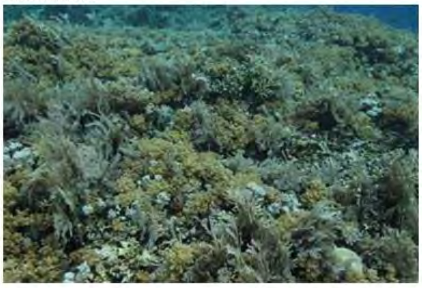
Rugosity: 3

HABITAT 29

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S29-2014



Soft coral:
Sinularia, Nephtea >50%

Hard coral:
<5%

Hydroids *(Aglaophenia)*> 15%

Substrate:
Rubble

Rugosity: 3

HABITAT 30

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Mix <10%

Soft coral:
Sinularia >60%

Hydroids *(Aglaophenia)* present

Rugosity: 3

HABITAT 31

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	**Pavement**	Sand	Mix Other

Lagoon	Terrace	Reef flat	**Crest**	Slope	Wall

Location: S28-2014

Hard Coral:
Mix <20%, encrusting dominant

Zoanthids, encrusting sponges

Substrate:
Pavement (coralline)

Rugosity: 3

Low relief spur and grooves

HABITAT 32

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Bunaken jetty

Hard Coral:
Acropora br > 25%
Millepora <5%

Substrate:
Rubble and sand

Rugosity: 3

HABITAT 33

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Bunaken jetty

Hard Coral:
Porites (branching), *Montipora* > 40%

Substrate:
rubble and sand

Rugosity: 3

HABITAT 34

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Alungbanua lagoon

Hard Coral:
Anacropora > 80%

Substrate:
Sand, rubble

Rugosity: 3

HABITAT 35

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Alungbanua lagoon

Hard Coral:
Montipora &
Porites br > 40%

Substrate:
Rock, rubble, sand

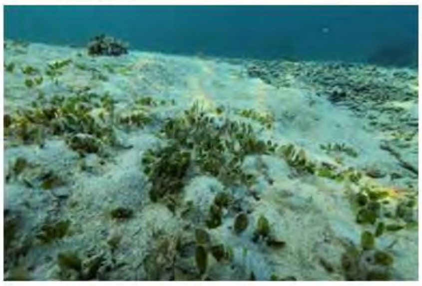
Rugosity: 4

HABITAT 36

Hard Coral	Soft Coral	Dead Coral	Algae	**Seagrass**	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Bunaken jetty , S1



Seagrass :
Halophilla < 20%

Substrate:
Sand & rubble

Rugosity: 1

HABITAT 37

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	**Sponge**	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Alungbanua lagoon

<u>Sponge:</u>
Haliclona >30 %

<u>Substrate:</u>
rubble , terrigeneous sand

<u>Rugosity:</u> 2

HABITAT 38

Hard Coral	Soft Coral	Dead Coral	**Algae**	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: S24-2014

<u>Algae:</u>
Branching coralline >50%
Halimeda present

Seagrass present

<u>Substrate:</u>
Pavement

<u>Rugosity:</u> 2

HABITAT 39

Hard Coral	Soft Coral	Dead Coral	**Algae**	**Seagrass**	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: S24-2014

<u>Algae:</u>
Coralline >50%

<u>Seagrass:</u>
<20%

<u>Substrate:</u>
Pavement, rubble

<u>Rugosity:</u> 2

HABITAT 40

Hard Coral	Soft Coral	Dead Coral	**Algae**	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location:

<u>Algae:</u>
Turbinaria >50%

<u>Hard Coral:</u>
Goniastrea, Platygyra <10%

<u>Substrate:</u>
Rock, small boulder

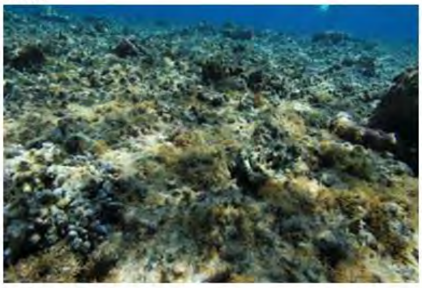
<u>Rugosity:</u> 2

HABITAT 41

Hard Coral	Soft Coral	Dead Coral	**Algae**	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location:



<u>Hard Coral:</u>
Present

<u>Algae:</u>
>30%

<u>Substrate:</u>
Rubble (cemented)

<u>Rugosity:</u> 2

HABITAT 42

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: S1-2014

<u>Hard Coral:</u>
Porites dominant, *Isopora* > 20%

Soft coral, sponge, dead coral present

<u>Substrate:</u>
Pavement , rubble

<u>Rugosity:</u> 3

HABITAT 43

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S24-2014

Hard Coral:
Goniastrea > 10%

Sponge present

Substrate:
Pavement with terrigeneous sand

Rugosity: 2

HABITAT 44

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014

Hard Coral:
Porites > 15% (micro-atolls)

Substrate:
Pavement, sand, rubble

Rugosity: 3

HABITAT 45

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S3-2014

Hard Coral:
H. coerulea, Porites, Isopora > 15%

Substrate:
Pavement

Rugosity: 3

HABITAT 47

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S5-2014

Hard Coral:
Montipora, Porites >30%

Substrate:
Pavement , rubble

Rugosity: 3

HABITAT 46

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S7-2014

Hard Coral:
Acropora dominant > 15%, *Isopora, Goniastraea*

Substrate:
Pavement

Rugosity: 3

HABITAT 48

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014

Hard Coral:
Massive >20%, *Heliopora* present

Soft Coral:
Xenia

Algae:
Turbinaria, turf algae

Substrate:
Rubble

Rugosity: 2

HABITAT 49

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014

Hard Coral:
Montipora, Goniastrea, Porites, etc. > 30%

Substrate:
Rubble (cemented)

Rugosity: 2

HABITAT 50

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Panorama

Hard Coral:
Montipora (dominant, branching and encrusting), *Acropora*, etc. >40%

Algae:
Turbinaria, turf algae

Substrate:
Rock, rubble

Rugosity: 3

HABITAT 51

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Mix, *Heliopora*> 50%

Substrate:
Rubble (cemented)

Algal turf

Rugosity: 2

HABITAT 52

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:T4-2016

Hard Coral:
Mix >50%

Substrate:
Pavement, rubble, sand

Rugosity: 3

HABITAT 53

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Massive corals > 20%

Substrate:
Rubble, rock

Rugosity: 3

HABITAT 54

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: T12-2016

Hard Coral:
Porites cylindrica, Goniastrea, Montipora <30%

Sponge:
Phyllospongia present

Substrate:
Small boulder, pavement, sand,

Rugosity: 3

HABITAT 55

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S9-2014

Hard Coral:
Mix, *Heliopora*
<30%

Soft Coral:
Xenia, Sinularia

Substrate
Rubble, pavement, rock

Rugosity: 3

HABITAT 56

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014

Hard Coral:
Heliopora, massive corals
>20%

Soft Coral:
Xenia, Lobophytum

Substrate:
Rubblem rock

Rugosity: 3

HABITAT 57

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Porites, Goniastrea, Isopora, Acropora (tables) >30%

Substrate:
Rock, pavement

Rugosity: 4

HABITAT 58

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014

Hard Coral:
Porites, mix> 25%

Soft Coral:
Sinularia >5%

Substrate:
Pavement , sand, rubble

Rugosity: 3

HABITAT 59

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Bastianos

Hard Coral:
Porites > 30%

Dead *Porites* > 20%

Substrate:
Rubble, sand

Rugosity: 3

HABITAT 60

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Bastianos

Hard Coral:
Massive *Porites, P. cylindrica* > 50%

Soft coral:
Sinularia

Substrate:
Rubble

Rugosity: 3

HABITAT 61

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Porites

Dead Coral:
Porites >50%

Substrate:
Pavement

Rugosity: 3

HABITAT 62

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Mix, massive dominant> 50%

Substrate:
Pavement , rock

Rugosity: 3

HABITAT 63

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Mix encrusting, digitate, and small massive >30%

Soft coral:
Lobophytum, *Xenia*, *Sinularia*

Algae:
Turbinaria

Substrate:
Pavement , rock

Rugosity: 3

HABITAT 64

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Massive corals *Heliopora* >15%

Substrate:
Small boulder

Rugosity: 3

HABITAT 65

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Porites, mix > 60%

Substrate:
Sand, rock

Rugosity: 3

HABITAT 66

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S16-2016

Hard Coral:
Porites lutea dominant, *Porites cylindrica*, *Montipora* br., *Heliopora* >60%

Soft coral:
Lobophytum

Rugosity: 3

HABITAT 67

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S15-2014

Dead coral:
Heliopora <30%

Hard Coral:
H. coerulea,
Porites > 30%

Turf algae

Rugosity: 3

HABITAT 68

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Montipora > 80%

Dead coral:
Montipora <20%

Rugosity: 3

HABITAT 69

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S13-2014

Hard Coral:
Montipora >80%

Substrate:
Sand

Rugosity: 3

HABITAT 70

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Montipora > 95%

Rugosity: 4

HABITAT 71

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S19-2014

Hard Coral:
Porites cylindrica,
Montipora, *Acropora*
table, etc. >70%

Soft coral:
Nephtea

Sponge:
Phyllospongia
present

Substrate:
Sand

Rugosity: 4

HABITAT 72

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Montipora >50%

Dead coral:
Montipora <20%

Turf algae,
cyanobacteria

Substrate:
Sand, rubble

Rugosity: 3

HABITAT 73

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Acropora >40%

Substrate:
Rubble, sand

Seagrass present

Rugosity: 4

HABITAT 74

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S21-2014

Hard Coral:
Montipora >80%

Seagrass:
Enhalus <10%

Rugosity: 3

HABITAT 75

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: T11-2016

Hard Coral:
Heliopora coerulea <15%

Dead *H. coerulea* >30%

Substrate:
Rubble

Rugosity: 3

HABITAT 76

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S16-2014

Dead Coral:
Porites > 50%

Hard coral:
Porites,
Montipora,
Heliopora <20%

Substrate:
Rock, rubble, small boulder

Rugosity: 3

HABITAT 77

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S23-2014

Dead Coral:
Porites > 70%

Hard coral:
<5%

Substrate:
Boulder, rock

Turf algae

Rugosity: 3

HABITAT 78

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S15-2016

Dead Coral:
Heliopora >90%

Hard coral:
Heliopora < 10%

Turf algae

Rugosity: 3

HABITAT 79

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Dead Coral:
Montipora > 80%

Hard coral:
Montipora, massive forms <5%

Soft coral:
Xenia present

Rugosity: 2

HABITAT 80

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S8-2014

Substrate:
Pavement (beach rock), sand

Rugosity: 1

HABITAT 81

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Substrate:
Pavement, sand

Algal turf

Rugosity: 1

HABITAT 82

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location S8-2014:

Substrate:
Pavement, small boulders

Massive, encrusting corals present

Sponge present

Rugosity: 1

HABITAT 83

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S8-2014

Substrate:
Pavement and small boulders

Massive corals present

Rugosity: 2

HABITAT 84

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S20-2014

Hard corals:
Porites, Goniastrea <5%

Substrate:
Pavement with terrigeneous sand

Rugosity: 2

HABITAT 85

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014

Hard Coral:
Acropora, Porites, Isopora <15%

Substrate:
Pavement, rubble, sand

Rugosity: 3

HABITAT 86

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Mix <5%

Soft coral:
Sinularia, Lobophytum <15%

Sponge present

Substrate:
Pavement, rock

Rugosity: 2

HABITAT 87

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Bunaken North

Hard Coral:
Pocillopora <15%

Substrate:
Pavement with turf algae

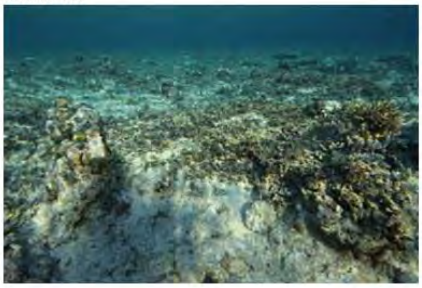
Rugosity: 2

HABITAT 88

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014



Hard Coral:
Porites, Acropora <10%

Substrate:
Rubble, Pavement, rock

Rugosity: 2

HABITAT 89

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014

Substrate:
Boulders, rubble

Rugosity: 2

HABITAT 90

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014

Hard Coral:
Porites <10%

Soft Coral:
Xenia

Algae:
Turbinaria, turf algae, cyanobacteria

Substrate:
Rubble

Rugosity: 2

HABITAT 91

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: Pangalisang

Hard Coral: *Goniastrea, Porites* <20%

Substrate: Rock, rubble

Rugosity: 3

HABITAT 92

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: S5-2014

Seagrass: Mix, present

Algae: *Halimeda* present

Substrate: Rubble

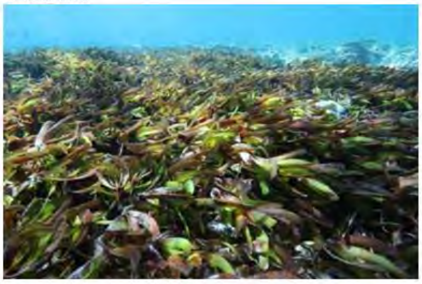
Rugosity: 1

HABITAT 93

Hard Coral	Soft Coral	Dead Coral	Algae	**Seagrass**	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: S3-2014



Seagrass: *Thalassodendron ciliatum*

Substrate: Small boulder

Rugosity: 1

HABITAT 94

Hard Coral	Soft Coral	Dead Coral	Algae	**Seagrass**	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: S5-2014

Hard Coral: *Montipora* >50%

Seagrass: Mix >25%

Subtrate: Sand

Rugosity: 3

HABITAT 95

Hard Coral	**Soft Coral**	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location: Jetty

Hard Coral: *Isopora, Porites* <10%

Soft coral: *Sinularia* >60%

Substrate: Sand, rock

Rugosity: 3

HABITAT 96

Hard Coral	**Soft Coral**	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	**Reef flat**	Crest	Slope	Wall

Location:

Hard Coral: <5%

Soft coral: *Sinularia, Lobophytum* >70%

Substrate: Pavement

Rugosity: 3

HABITAT 97

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral: *Montipora, massive forms* <40%

Soft coral: *Xenia* >25%

Rugosity: 2

HABITAT 98

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral: *Porites, Isopora, Montipora* >25%

Soft coral: *Sinularia* >30%

Substrate: Sand, rock

Rugosity: 4

HABITAT 99

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S10-2014

Hard Coral: *Isopora, Porites* dominant <10%

Substrate: Sand, rubble, scattered rock

Rugosity: 3

HABITAT 100

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: D14-2015

Hard Coral: Mix <15%

Dead coral: >15%

Substrate: Rock, sand

Rugosity: 4

HABITAT 101

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Rons point

Hard Coral: 40% Mix > 20%

Soft coral: Lobophytum

Sponge> 5%

Gorgonians present

Substrate: Rock, rubble

Rugosity: 4

HABITAT 102

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: D14-2015

Hard Coral: *Isopora* dominant >15%

Substrate: Rock, boulder, rubble, sand

Rugosity: 4

HABITAT 103

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Sachiko

<u>Hard Coral:</u>
Isopora, Porites >15%

<u>Soft coral:</u>
Sinularia >20%

Hydroids present

<u>Substrate:</u>
Rock, boulder, rubble, sand, dead large *Porites*

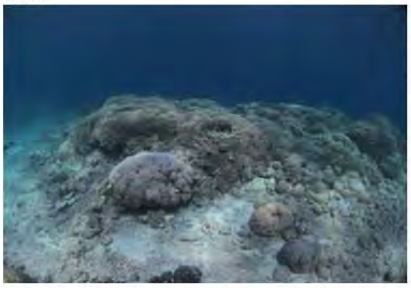
<u>Rugosity:</u> 4

HABITAT 104

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:



<u>Hard Coral:</u>
Mix > 40%

<u>Substrate:</u>
Rock, rubble

<u>Rugosity:</u> 3

HABITAT 105

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

<u>Hard Coral:</u>
Isopora dominant, mix > 10%

Sponges > 10%

<u>Substrate:</u>
Rock, rubble, sand

<u>Rugosity:</u> 4

HABITAT 106

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

<u>Hard Coral:</u>
Isopora, Porites dominant, foliose > 40%

<u>Substrate:</u>
Rubble, rock, sand

<u>Rugosity:</u> 4

HABITAT 107

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: D1-2015

<u>Hard Coral:</u>
Mix > 70%

<u>Sponges:</u>
Xestospongia

<u>Substrate:</u>
Rock

<u>Rugosity:</u> 4

HABITAT 108

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

<u>Hard Coral:</u>
Echinopora dominant <50%

<u>Sponge:</u>
Xestospongia, Lufariella, etc.

<u>Substrate:</u>
Rock, rubble

<u>Rugosity:</u> 4

HABITAT 109

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral: %
Mix branching dominant, foliose, massive >75%

Substrate:
Rock

Rugosity: 4

HABITAT 110

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Echinopora, Mycedium, Acropora, etc. > 80%

Sponge:
Xestospongia

Rugosity: 4

HABITAT 111

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Foliose and mix forms > 50%

Sponge:
Xestospongia

Substrate:
Rock

Rugosity: 4

HABITAT 112

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Foliose forms dominant, mix <30%

Sponge:
Xestospongia Lufariella, etc.

Dead coral:
>40%

Rugosity: 4

HABITAT 113

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Galaxea >80%

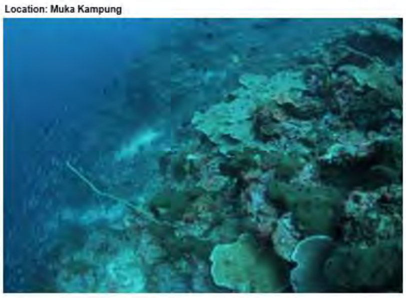
Rugosity: 4

HABITAT 114

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Muka Kampung



Hard Coral:
Plating corals dominant, mix >40%

Sponge:
Luffariella >5%

Substrate:
Rock

Rugosity: 4

HABITAT 115

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Plating dominant, mix forms >30%

Sponges:
Mix > 5%

Soft coral:
Lobophytum

Hydroid > 5%

Rugosity: 4

HABITAT 116

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Mix forms > 60%

Substrate:
Rock, sand in gullies

Rugosity: 4

HABITAT 117

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
<10%

Sponge <10%

Antipatharian

Substrate:
Rock

Rugosity: 2

HABITAT 118

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S12-2014

Hard Coral:
Mix <20%

Soft corals <15%

Hydroids <5%

Substrate:
Pavement , rock, rubble

Rugosity: 3

HABITAT 119

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: D3-2014

Hard Coral:
Plating/massive dominant, mix >50%

Substrate:
Rock, sand

Rugosity: 4

HABITAT 120

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Fukui

Hard Coral:
Foliose corals <15%

Dead coral:
>60%

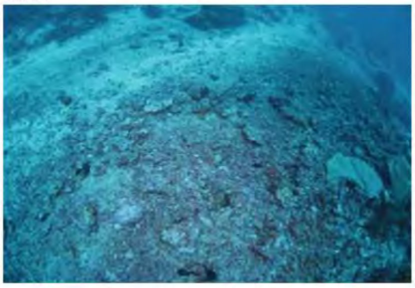
Rugosity: 3

HABITAT 121

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	**Slope**	Wall

Location:



Substrate:
Rubble, sand

Rugosity: 2

HABITAT 122

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	**Slope**	Wall

Location: D7-2015

Hard Coral:
Mix <10%

Sponge:
Xestospongia present

Substrate:
Rubble, sand

Rugosity: 3

HABITAT 123

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	**Slope**	Wall

Location: S2-2104

Hard Coral:
Isopora, Porites cylindrica, mix < 20%

Hydroids present

Substrate:
Rubble, sand

Rugosity: 3

HABITAT 124

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	**Slope**	Wall

Location: Fukui

Hard Coral:
Recruits massive coral <5%

Substrate:
Rubble

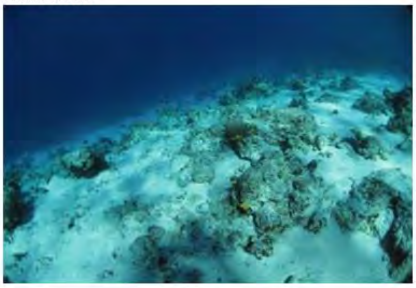
Rugosity: 1

HABITAT 125

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	**Sand**	Mix Other

Lagoon	Terrace	Reef flat	Crest	**Slope**	Wall

Location: D14-2015



Hard coral:
Present

Substrate:
Sand , scattered rock

Rugosity: 3

HABITAT 126

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	**Sand**	Mix Other

Lagoon	Terrace	Reef flat	Crest	**Slope**	Wall

Location: D14-2015

Hard Coral:
Mix > 10%

Substrate:
Sand, small rock

Rugosity: 3

HABITAT 127

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S8-2014

Algae:
Phaeophyceae
>75%

Seagrass:
Mix<20%
Patchy

Substrat:
Sand, rubble

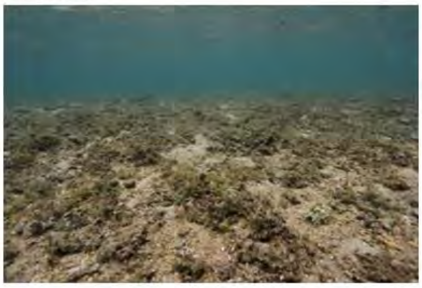
Rugosity: 2

HABITAT 128

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S24-2014



Algae:
Turf: >50%

Substrate:
Pavement
terrigeneous sand

Rugosity: 1

HABITAT 129

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Algae:
Phaeophyceae
>40%

Seagrass:
Present

Substrate:
Pavement, rubble, sand

Rugosity: 2

HABITAT 130

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Algae:
Phaeophyceae (Bornetella), Acanthophora
>40%

Seagrass:
Present

Substrate:
Pavement, rubble

Rugosity: 2

HABITAT 131

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S3-2014

Algae:
Phaeophyceae
>80%

Seagrass:
Present

Substrate:
Pavement, rubble

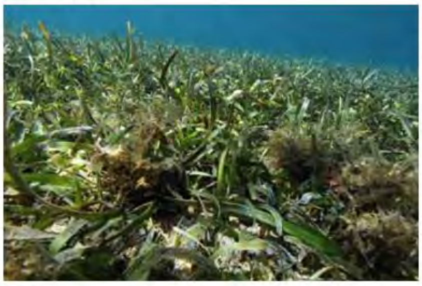
Rugosity: 2

HABITAT 132

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014



Seagrass:
Mix > 60%
Canopy <40cm
Continuous

Algae:
Phaeophyceae > 15%

Substrat:
Sand

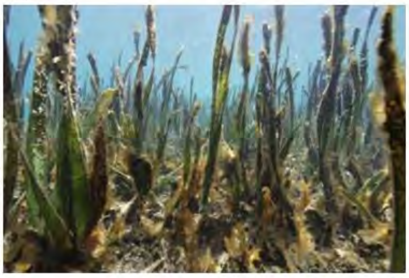
Rugosity: 2

HABITAT 133

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:



Seagrass:
Mix > 40%
Enhalus acoroides dominant with epiphytes
Patchy
Canopy>40cm

Algae:
Cyanobacteria > 15%

Substrat:
Sand, terrigenous mud

Rugosity: 2

HABITAT 134

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S2-2014

Seagrass:
Mix > 60 %
Canopy <20 cm
Continous

Algae:
Bornetella > 10%

Hard Coral:
present

Substrat:
Sand, rubble

Rugosity: 2

HABITAT 135

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S17-2014

Seagrass:
Mix > 60%
Continuous
Canopy<25cm

Algae:
Filamentous green >30%

Substrat:
Sand, rubble

Rugosity: 2

HABITAT 136

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S21-2014

Hard Coral:
Lobophyllia>70%

Seagrass:
Enhalus <20%

Rugosity: 2

HABITAT 137

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Dead Coral:
Montipora with Turf >40%

Seagrass:
Mix <30%

Substrat:
Rubble, dead coral

Rugosity: 2

HABITAT 138

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S10-2015

Sponge:
Phyllospongia

Hard Coral:
Present

Substrate:
Sand (terrigeneous), rubble, rock with turf algae

Rugosity: 2

HABITAT 139

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	**Pavement**	**Sand**	Mix Other

Lagoon	**Terrace**	Reef flat	Crest	Slope	Wall

Location: S8-2014

Algae;
Turf on rubble, very low density macroalgae

Substrate:
Sand on pavement, rubble

Rugosity: 1

HABITAT 140

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	**Pavement**	Sand	Mix Other

Lagoon	**Terrace**	Reef flat	Crest	Slope	Wall

Location: S32-2014

Hard Coral:
Porites present

Sponge:
Phyllospongia

Substrate:
Sand and turf on pavement

Rugosity: 1

HABITAT 141

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	**Terrace**	Reef flat	Crest	Slope	Wall

Location: S4-2016

Seagrass:
Enhalus acoroides, Thalassia <30%

Substrate:
Rubble > 65%

Rugosity: 2

HABITAT 142

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	**Terrace**	Reef flat	Crest	Slope	Wall

Location: S 5-2014

Substrate: Rubble (cemented) > 95%

Seagrass: Present

Rugosity: 1

HABITAT 143

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	**Rubble**	Pavement	Sand	Mix Other

Lagoon	**Terrace**	Reef flat	Crest	Slope	Wall

Location:

Hard Coral:
Porites >5%

Seagrass:
Present

Substrate:
Rubble > 90%

Rugosity: 2

HABITAT 144

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	**Sand**	Mix Other

Lagoon	**Terrace**	Reef flat	Crest	Slope	Wall

Location: S21-2014

Substrate:
Terrigeneous mud = 100%

Rugosity: 1

HABITAT 145

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S19-2014

Seagrass: Present

Substrate: Sand = 100%

Rugosity: 1

HABITAT 146

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S17-2014

Substrate: Mud, sand with rubble, algal turf

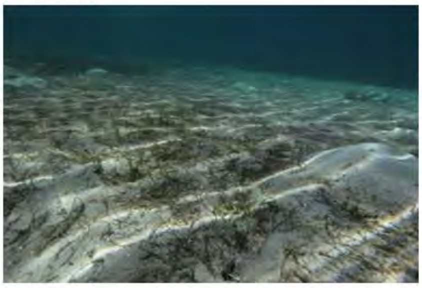
Rugosity: 1

HABITAT 147

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014



Seagrass: *Halodule* < 15%

Substrate: Sand

Rugosity: 1

HABITAT 148

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S11-2014

Seagrass: *Halodule* < 40%

Substrate: Sand with mangrove roots

Rugosity: 2

HABITAT 149

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S20-2014

Seagrass: Mix > 30%

Substrate: Terrigeneous mud

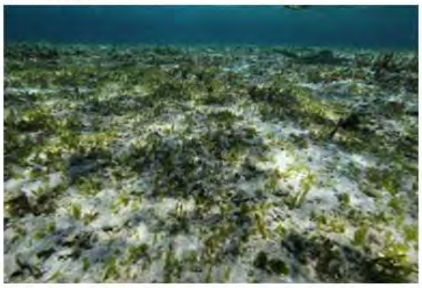
Rugosity: 1

HABITAT 150

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S6-2014



Seagrass: *Halophila* > 30% Continuous

Substrate: Sand & rubble

Rugosity: 1

HABITAT 151

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S10-2014

Seagrass:
Enhalus < 15%
Patchy

Substrate:
Sand, rubble, pavement

Rugosity: 2

HABITAT 152

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S6-2014

Seagrass:
Mix >20%, <50%
Canopy , 20%
Patchy

Substrate:
Sand

Rugosity: 2

HABITAT 153

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Seagrass:
Mix <50%, patchy
Canopy >30 cm

Substrate:
Terrigeneous sand

Rugosity: 2

HABITAT 154

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S6-2014

Seagrass:
Mix <50%
Continuous
Canopy <20cm

Substrate:
Sand

Rugosity: 2

HABITAT 155

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014

Hard Coral:
Massive <10 %
Porites, Alveopora

Seagrass:
Mix < 70%
Canopy < 20cm
Continuous

Substrate:
Rubble with sand

Rugosity: 2

HABITAT 156

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Seagrass:
Mix >40%
Canopy < 20 cm
Continuous

Sponge:
Dysidea >10%

Substrate:
Sand

Rugosity: 2

HABITAT 157

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S2-2014

Seagrass:
Mix >70%
Canopy <20cm
Continuous

Substrate:
Sand

Rugosity: 2

HABITAT 158

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S22-2014

Seagrass:
Mix >80%
Thallasodendron dominant
Canopy >40cm
Patchy

Substrate:
Rock, rubble

Rugosity: 2

HABITAT 159

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S1-2014

Seagrass:
Mix > 80%
Canopy > 40 cm
Continuous

Substrate:
Sand

Rugosity: 2

HABITAT 160

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S6-2014

Seagrass:
Mix >90%
Enhalus acoroides dominant
Canopy >40 cm
Continuous

Substrat:
Sand

Rugosity: 2

HABITAT 161

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S5-2014

Hard Coral:
Montipora, Acropora >30%

Seagrass:
Enhalus acoroides, Thalassia >40%
Canopy>40cm

Substrate:
Rubble, sand

Rugosity: 3

HABITAT 162

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S6-2014

Seagrass:
Mix >45%
Canopy <20cm
Continuous

Soft Coral:
Xenia > 15%

Substrate:
Rubble, sand

Rugosity: 2

HABITAT 163

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S18-2014

Hard Coral:
Heliopora coerulea > 5%

Seagrass:
Mix > 45%
Thalassia dominant

Substrat:
Rubble

Rugosity: 3

HABITAT 164

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S6-2014

Hard Coral:
Montipora >50%

Seagrass:
Mix < 50%
Patchy
Canopy <40cm

Substrat:
Rubble

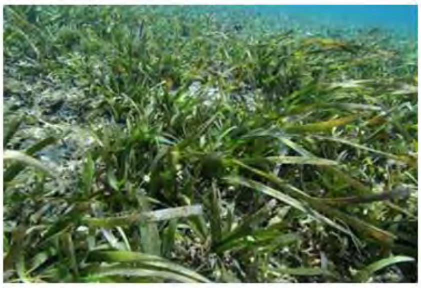
Rugosity: 2

HABITAT 165

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S4-2014



Seagrass:
Enhalus >70%

Substrate:
Rubble, small boulders

Rugosity: 2

HABITAT 166

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: S2-2014

Seagrass:
Thalassia <30%
Canopy<20%3

Substrate:
Rubble - sand

Rugosity: 2

HABITAT 167

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Mandolin

Hard Coral:
Montipora, Porites, etc. >50%

Sponge:
<15%

Algae:
Mix <10%

Ascidians

Substrate:
Rock

Rugosity: 4

HABITAT 168

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Pangalisang

Hard Coral:
Montipora, Platygyra, etc. >50%

Sponge:
<5%

Substrate:
Rock

Rugosity: 4

HABITAT 169

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Raymonds Point

Hard Coral:
Mix>40%

Antipatharia, sponges, ascidians

Algae:
Mix <10%

Substrate:
Rock, rubble

Rugosity: 4

HABITAT 170

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Raymonds point

Hard Coral:
Mix>40%

Antipatharia, sponges, gorgonians, ascidians, hydroids

Algae:
Mix <10%

Substrate:
Rock

Rugosity: 4

HABITAT 171

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location:

Hard Coral: 60%
Platygyra, Porites, Pocillopora, Diploastrea

Sponge: 40%

Rugosity: 4

HABITAT 172

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Raymonds point

Anthipatarians, sponges, gorgonians, soft corals (incl. *Dendronephtya)*, ascidians

Hard coral:
Mix <10%

Algae:
Mix <10%

Substrate:
Rock

Rugosity: 4

HABITAT 173

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Sachiko

Gorgonians, sponges, soft corals anthipatarians, ascidians

Hard coral:
Mix >20%

Algae:
Mix <10%

Substrate:
Rock

Rugosity: 4

HABITAT 174

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Sachiko

Hard Coral:
Mix <30%

Sponge:
<15%

Algae:
Mix <10%

Ascidians, gorgoniansm, soft coral, hydrozoans

Substrate:
Rubble, Rock

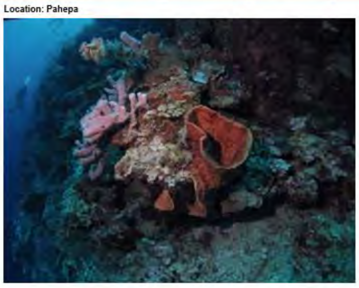
Rugosity: 4

HABITAT 175

Hard Coral	Soft Coral	Dead Coral	Algae	Seagrass	Sponge	Rubble	Pavement	Sand	Mix Other

Lagoon	Terrace	Reef flat	Crest	Slope	Wall

Location: Pahepa



Sponges:
Mix > 15%

Gorgonians, soft corals anthipatarians, ascidians

Hard coral:
Mix >20%

Algae:
Mix <10%

Substrate:
Rock

Rugosity: 4

APPENDIX III
POLYGON COMPOSITION

The composition of the polygons is given below for each geomorphological zone (WALL, LAGOON, SLOPE, CREST, TERRACE, REEF FLAT). In the following tables, 1 indicates that the habitat (column X) is included in the polygon (line Y), 0 or nothing that it is not.

WALL													
Polygon	167	168	169	170	171	172	173	174	175	*109*	*114*	*115*	*116*
182	1	1			1				1				
183		1			1				1		1	1	1
184					1				1				
185		1	1	1	1		1	1		1			
186		1	1	1	1		1	1		1	1		1
187	1		1	1	1								
188		1			1		1		1				
189		1			1				1				
190	1	1			1				1				
191	1				1		1	1					
192			1	1	1	1							
193	1				1		1	1					
194	1				1		1	1					

LAGOON									
Polygon	32	33	34	35	36	37	153	158	159
28					1				
29	1		1	1	1				
30	1		1			1			
31					1				
32			1		1	1			
33	1				1				
34	1				1				
35							1	1	1
36					1				
37		1							

															SLOPE													
Polygon	99	100	101	102	103	104	105	106	107	108	*109*	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126
99				1		1	1	1												1								
100																							1	1	1			
101			1						1					1						1								
102	1	1																						1			1	1
103	1																						1			1	1	1
104			1																									
105	1																						1				1	
106	1															1		1			1							
107																		1										
108																					1							
109																1	1	1			1		1	1				
110																					1			1				
111															1													
112																			1				1		1			
113					1											1			1	1					1			
114																		1			1			1				
115					1																							
116									1	1		1	1	1	1							1						

	CREST																																			
Polygon	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	*87*	*96*	*103*	*93*	*113*
1					1																		1													
2					1	1			1		1	1									1	1					1	1	1	1						
3		1													1		1																			
4		1					1	1									1			1	1															
5										1		1	1	1			1																			
6					1																	1														
7					1	1															1	1	1													
8							1	1						1			1			1	1															
9					1	1			1											1	1	1	1			1	1	1	1					1		
10																															1	1	1	1		
11								1			1	1						1			1	1														
12					1	1														1	1					1								1		
13								1		1			1	1			1																			
14																								1	1											
15					1											1					1															
16																																				1
17																1							1	1	1											
18	1		1	1											1																					
19					1											1	1		1				1	1	1											
20	1		1	1											1																					
21		1	1	1											1									1												
22	1			1																																
23																											1	1	1							
24																																			1	
25																				1	1						1	1	1							
26	1																																			
27																									1	1										

		TERRACE																																										
Polygon		127	128	129	130	131	132	133	134	135	136	137	139	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	159	160	161	162	163	164	165	166	*38*	*39*	*97*	*70*	*72*	*73*
w1	117		1	1				1																																		
w2	118					1	1																																			
w3	119													1	1													1											1						
w4	120					1																									1	1												
w5	121																	1		1	1	1	1		1		1																				
w6	122		1											1	1	1													1															
w7	123																													1	1													
w8	124											1																					1	1	1	1	1							
w9	125					1			1																							1	1												
w10	126												1					1	1				1		1		1																				
w11	127		1	1												1																							1						
w12	128			1	1																																					
w13	129	1																										1									1								
w14	130												1										1		1																				
w16	131																													1														
w17	132													1	1																									1						
w18	133								1																			1							1											
w19	134												1	1																													
w20	135																														1	1	1			1										
w21	136	1										1																					1	1		1	1							
w22	137													1															1					1										
w23	138		1																			1							1																
w24	139													1	1										1			1																		
w26	140																								1			1																		
w27	141																																	1												
w28	142			1																																		1						
w29	143																																							1						
w30	144																																					1			1	1	1				

(Terrace continued next page)

		TERRACE																																								
Polygon		127	128	129	130	131	132	133	134	135	136	137	139	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	159	160	161	162	163	164	165	166	*38*	*39*	*97*	*70*	*72*	*73*
c1	145							1									1			1	1	1																						
c2	146															1						1				1													1	1				
c3	147							1																							1													
c4	148																	1	1	1																								
c6	149																											1		1						1						1	1	1
c7	150																											1																
c8	151						1	1		1																1																		
c9	152															1			1																							1	1	1
c10	153																															1	1											
c11	154										1													1																				
c12	155							1																																				
c13	156																	1					1																					
c14	157						1																									1												
c15	158																							1			1	1																
c16	159												1											1	1													1						
c17	160																														1	1	1											
c18	161													1	1										1		1	1																
c19	162							1									1					1																						
c20	163																			1							1																	
c21	164							1																								1												
E1	165			1	1										1																							1						
E2	166	1	1	1		1																							1	1														
E3	167													1																								1						
E5	168							1																		1																		
E6	169																																1				1							
E7	170																														1													
E8	171																											1							1									
E9	172																								1	1				1														
E10	173				1									1	1																													
E11	174		1		1	1																																						
E12	175																		1	1	1	1																						
E13	176																																					1						
E14	177																																				1							
E15	178												1						1																									
E16	179			1	1									1																														
E17	180	1		1			1																																					
E18	181				1										1																							1						

REEF FLAT

Polygon	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	98	127	129	130	131	132	138	139	139	140	141	142	146	155	155	159	159	161	162	164	165	166
38														1			1							1																												1																											
39								1						1																												1	1	1					1	1																													
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49																																										1	1																																					
50						1		1							1	1	1	1	1					1	1																																																						
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56			1	1														1					1									1																																																	
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61			1		1														1	1	1	1															1	1								1										1		1																						
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67																										1										1																																											
68																										1	1	1									1																																										
69																																																																									1		1					
70										1																			1						1																																										1	1	

(REEF FLAT continued next page)

Polygon	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79
71																											1	1								1				
72																										1	1					1								
73																																								
74																													1	1									1	1
75										1			1																											
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98						1										1	1																			1				

Polygon	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	98	127	129	130	131	132	138	139	139	140	141	142	146	155	155	159	159	161	162	164	165	166
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94																															1						1		
95																																							
96																					1	1	1																
97																												1											1
98																																							

APPENDIX IV

AN EXAMPLE OF ACCURACY ASSESSMENT

SLOPE

Polygon	99	100	101	102	103	104	105	106	107	108	*109*	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126
112																			1				1		1			

CREST

Polygon	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	*87*	*96*	*103*	*93*	*113*
6					1																	1														
8							1	1						1			1			1	1															

TERRACE

Polygon	127	128	129	130	131	132	133	134	135	136	137	139	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	159	160	161	162	163	164	165	166	*38 3997707273*
118						1	1																															
120						1																									1	1						
121																1		1	1	1	1		1		1													

REEF FLAT

Polygon	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83
49																																										1	1	
50						1		1							1	1	1	1	1					1	1																			
51							1	1																																		1	1	
53						1		1							1	1	1	1	1					1	1																			

Error matrices:

The following small tables indicate if the mapped habitat was really there (1) or not (0).

6	Mapped	
	5	21
True	1	0

8	Mapped					
	7	8	14	17	20	21
True	0	0	0	0	1	1

49	Mapped	
	81	82
True	1	1

50	Mapped								
	45	47	54	55	56	57	58	63	64
True	1	1	0	0	0	0	0	1	1

51	Mapped			
	46	47	81	82
True	0	1	1	1

53	Mapped								
	45	47	54	55	56	57	58	63	64
True	0	0	0	0	1	1	1	0	0

112	Mapped		
	117	121	123
True	0	1	1

118	Mapped	
	132	133
True	1	1

120	Mapped		
	132	160	161
True	1	1	0

121	Mapped						
	144	146	147	148	149	151	153
True	0	0	1	1	0	0	0

A simple measure of accuracy, similar to user's accuracy, would be the number of "1" divided by the total number of habitats according to mapping, which gives:

Polygon 112: Accuracy = 2/3
Polygon 6: Accuracy = 1/2
Polygon 8: Accuracy = 2/6
Polygon 118: Accuracy = 1/1=100%
Polygon 120: Accuracy = 2/3
Polygon 121: Accuracy = 2/7
Polygon 49: Accuracy = 1/1
Polygon 50: Accuracy = 4/9
Polygon 51: Accuracy = 3/4
Polygon 53: Accuracy = 3/9

The producer's accuracy is always 100%.

EXTENDED ABSTRACT

The INDESO (Indonesian Development of Space Oceanography) project in collaboration between the Indonesian government (Ministry for Marine Affairs and Fisheries - MMAF) and the French company CLS (Collecte Localisation Satellite) promote the use of space technologies for monitoring the Indonesian coasts and seas. INDESO applications are divided into 1) Sustainable Coastal Development, and 2) Fisheries and Aquaculture. The former category includes *Coral Reef Monitoring, ICZM & Mangroves, oil spill monitoring*. The latter includes *Fight IUU Fishing, Monitor Fish stocks, Shrimp farming* and *Seaweed farming*. This thesis is part of the *Coral Reef Monitoring* Application, led by IRD (Institut de Recherche pour le Développement). The main objective was to determine if coral reef habitats in Bunaken Island (BI) in North Sulawesi are resilient, using i) newly designed habitat maps, ii) *in-situ* data and a unique 15-year time series of satellite images from different very high spatial resolution (VHR) sensors, iii) ancillary data that could explain the detected changes. Indeed, understanding coral reef habitat resilience is seen as a priority, in particular to perceive the effects of both management actions and stressors. The thesis includes 3 main chapters, each corresponding to a separate publication.

First, an extremely detailed habitat map of the reefs around BI was created using a 2m resolution Geoeye-1 image and ground-truth data collected in 2014-2015. The objective was to create a map that makes justice to the complexity and richness of habitats found around the small BI (5 km^2 of reefs). A habitat map of 194 polygons was created by photo-interpretation, using simple methods and toolboxes available in the ENVI software. Each polygon received a list of possible habitats found among a list of 175 habitats identified in 6 geomorphological zones (Wall, Slope, Crest, Reef Flat, Terrace and Lagoon). The product and the information (list of habitats per polygon) could be evaluated using control ground-truth data. These observations yielded an error matrix for each polygon according to the differences of presence/absence between mapped habitats and *in situ* habitat observations.

Second, we witnessed coral mortality in March 2016, and documented the event for several of the habitats identified above. In September 2015, altimetry data shows that sea level was at its lowest in the past 12 years due to the strongest El Niño on record, affecting the shallowest corals. In March 2016, BI displayed up to 85% mortality on reef flats dominated by *Porites, Heliopora* and *Goniastrea* corals with mortality rates depending on coral genus. Almost all reef flats experienced mortality, representing 30% of BI reefs. Altimetry data was used to map

sea level fall throughout Indonesia, suggesting that similar mortality could be widespread for Indonesian shallow reef flat communities. The altimetry historical records also suggest that such event was not unique in the past two decades, therefore rapid sea level fall could be more important in the dynamics and resilience of Indonesian reefs than previously thought.

Finally, time-series of VHR satellite imagery was used to characterize the long-term dynamics of BI habitats, especially on shallow reef flats, between 2001 and 2015. Lack of historical georeferenced ground-truth data pointed out to a scenario approach based on the monitoring of selected unambiguously-changing habitat polygons characterized *in situ* in 2014 and 2015. This allowed identifying representative scenario of changes and discussing BI resilience. Surprisingly, trajectories of coral patches were highly different even in a small spatial area. Coral communities dominated by different corals could appear stable, disappearing completely abruptly, disappearing slowly, or colonizing slowly or rapidly new substrates. In parallel, nearby seagrass beds were generally increasing in density and dimension across the studied period. These scenarios occurring simultaneously were identified in close vicinity, precluding the identification of a single general cause of changes that could affect the whole reef. Likely, very fine difference in reef topography, exposure to wind/wave and sea level variations are responsible for the variety of outcomes.

We concluded that BI demonstrates capacity for resilience and did not experience phase-shift, but a definitive diagnostic of Bunaken's resilience from imagery remains difficult to ascertain. Mapping precisely the variation in coral community trajectory shows that a particular reef can be a kaleidoscope of very different behaviors. These trajectories can not be fully captured without changing some monitoring paradigms. A combination of remote sensing observations (VHR for the reef themselves and other data for around the reefs), and in situ data remain the best strategy to understand better the dynamics of Indonesian coral reefs.

RESUMÉ ÉTENDU

Le projet INDESO (Développement de l'Océanographie Spatiale en Indonésie) en collaboration entre le gouvernement indonésien (Ministère des affaires maritimes et des pêches - MMAF) et la société française CLS (Collecte Localisation Satellite) promeut l'utilisation des technologies spatiales pour la surveillance des côtes et des mers indonésiennes. Le projet concerne (1) le développement durable des zones côtières, et (2) la pêche et l'aquaculture. Le premier volet comprend le suivi des récifs coralliens, la gestion intégrée de la zone côtière, les mangroves et la surveillance des rejets d'hydrocarbures. Le second comprend la lutte contre la pêche illégale, le suivi des stocks de poissons, l'élevage de crevettes et d'algues agricoles. Cette thèse fait partie du volet sur la surveillance des récifs coralliens, mené par l'IRD (Institut de Recherche pour le Développement). L'objectif principal était de déterminer si les habitats des récifs coralliens dans l'île de Bunaken (IB) dans le nord de Sulawesi sont résilients, en utilisant i) des cartes d'habitat nouvellement conçues, ii) des données in situ et une série chronologique unique de 15 ans d'images satellites de différents capteurs à très haute résolution (VHR), iii) des données auxiliaires qui pourraient expliquer les changements détectés. En effet, la compréhension de la résilience des habitats du récif corallien est considérée comme une priorité, en particulier pour percevoir les effets des mesures de gestion et de stress. La thèse comprend 3 grands chapitres, chacun correspondant à une publication distincte.

Tout d'abord, une carte extrêmement détaillée de l'habitat des récifs autour de IB a été créé en utilisant une image GeoEye-1 de résolution 2m et des données de vérité-terrain recueillies en 2014-2015. L'objectif était de créer une carte qui rende compte de la complexité et de la richesse des habitats trouvés pour une petite surface de 5 km^2 de récifs. Une carte d'habitats de 194 polygones a été créée par photo-interprétation, en utilisant des méthodes et outils simples disponibles dans le logiciel ENVI. Chaque polygone a reçu une liste d'habitats possibles établis parmi une liste de 175 habitats identifiés dans 6 zones géomorphologiques (tombant, pente, crête, platier, terrasse et lagon). Le produit et les informations (liste des habitats par polygone) peuvent être évalués en utilisant des données de contrôle de vérité-terrain. Ces observations aboutissent à une matrice d'erreur pour chaque polygone en fonction des différences de présence / absence entre les habitats cartographiés et les observations de l'habitat in situ.

Deuxièmement, nous avons observé une mortalité du corail en Mars 2016, et documenté l'événement pour plusieurs des habitats identifiés ci-dessus. En Septembre 2015, les données d'altimétrie montrent que la mer était à son niveau le plus bas au cours des 12 dernières années en raison du très fort événement El Niño en cours, ce qui a affecté les coraux les moins profonds. En Mars 2016, IB affiche une mortalité jusqu'à 85% sur les platiers où dominent les coraux *Porites*, *Heliopora* et *Goniastrea* avec des pourcentages de mortalité dépendant du genre. Presque tous les platiers récifaux ont connu une mortalité, ce qui représente 30% des récifs de IB. Les données altimétriques ont été utilisées pour cartographier la baisse du niveau de la mer sur toute l'Indonésie. Les résultats suggèrent qu'une mortalité similaire a pu se produire sur d'autres récifs indonésiens peu profonds. Les données historiques altimétriques suggèrent également que cet événement n'a pas été unique au cours des deux dernières décennies, et donc que la chute rapide du niveau de la mer pourrait être plus importante dans la dynamique et la résilience des récifs indonésiens qu'on ne le pensait.

Enfin, les séries chronologiques de l'imagerie satellitaire VHR ont été utilisées pour caractériser la dynamique à long terme des habitats de IB, en particulier sur les platiers peu profonds, entre 2001 et 2015. Le manque de données de terrain historiques géoréférencées nous a conduit vers une approche de scénarios basée sur le suivi d'une sélection de polygones d'habitat évoluant sans ambiguïté et caractérisés *in situ* en 2014 et 2015. Cela a permis d'identifier des scénarios représentatifs des changements et de discuter de la résilience de IB. Étonnamment, les trajectoires de communautés de corail sont très différentes même dans un espace restreint. Des communautés, dominées par différents genre de coraux, ont pu apparaître stables, disparaître complètement, brusquement ou lentement, ou coloniser lentement ou rapidement de nouveaux substrats. En parallèle, les herbiers à proximité se sont en général développés en taille et en densité dans la période étudiée. Ces scénarios qui se sont produits simultanément ont été identifiés dans des zones proches, ce qui empêche l'identification d'une seule cause générale des changements qui pourraient avoir une incidence sur l'ensemble du récif. Probablement, les différences subtiles de topographie, de l'exposition au vent / vagues et de variation du niveau de la mer sont responsables de la variété des résultats.

Nous avons conclu que IB démontre une capacité de résilience et n'a pas connu de déphasage, mais qu'un diagnostic définitif de la résilience de l'île de Bunaken reste difficile à déterminer par imagerie pour la période étudiée. La cartographie précise des modifications dans la communauté corallienne montre qu’un récif particulier peut être un kaléidoscope de comportements très différents. Ces trajectoires ne peuvent pas être totalement comprises sans changer certains paradigmes de surveillance. Une combinaison d'observations de télédétection (VHR pour les récifs eux-mêmes et d'autres données autour des récifs) et de données in situ reste la meilleure stratégie pour mieux comprendre la dynamique des récifs coralliens indonésiens.

FOREWORD

"I used to think the top environmental problems were biodiversity loss, ecosystem collapse and climate change. I thought that with 30 years of good science we could address those problems. But I was wrong. The top environmental problems are selfishness, greed and apathy. And to deal with those we need a spiritual and cultural transformation – and we scientists don't know how to do that." (***Gus Speth)***

In the much more complicated case of Sulawesi we can only indicate their general nature, since we now see the result, not of any single or recent change only, but of a whole series of the later revolutions which have resulted in the present distribution of land in the Eastern Hemisphere. (Wallace and Whitten, 2008)

SHORT ABSTRACT

In the frame of the INDESO (Indonesian Development of Space Oceanography) project, in collaboration between the Indonesian government and the French company CLS, the main objective of this thesis, led by IRD (Institut de Recherche pour le Développement), was to determine if coral reef habitats in Bunaken Island (BI) in North Sulawesi are resilient, using i) newly designed habitat maps, ii) *in-situ* data and a unique 15-year time series of satellite images from different very high spatial resolution (VHR) sensors, iii) ancillary data. Results include a very detailed BI map of 175 habitats. The influence of sea level fall on coral mortality during the 2015-2016 El Niño is shown and discussed using in situ and altimetry data. Finally, VHR time time-series highlighted very different trajectories of coral habitats in a small spatial domain, including coral community growth. As such, BI demonstrates capacity for resilience, although the studied period was too short to definitely conclude. Habitat trajectories cannot be fully understood without changing some monitoring paradigms, by using a combination of remote sensing observations and in situ data.

RESUMÉ COURT

Dans le cadre du projet INDESO (Développement de l'océanographie spatiale en Indonésie), en collaboration entre le gouvernement indonésien et la société française CLS, l'objectif principal de cette thèse, conduite par l'IRD (Institut de Recherche pour le Développement), était de déterminer si les habitats des récifs coralliens dans l'île de Bunaken (IB) au nord de Sulawesi sont résilients, en utilisant i) des cartes d'habitats récentes, ii) des données in situ et une série chronologique de 15 ans d'images satellites de capteurs très haute résolution (THR), iii) des données auxiliaires. Les résultats comprennent une carte très détaillée de IB (175 habitats). L'influence de la chute du niveau de la mer sur la mortalité des coraux pendant l’événement El Niño de 2015-2016 est présentée à partir des données in situ et d’altimétrie. Enfin, la série temporelle THR met en évidence des trajectoires très différentes des habitats coralliens, dont une extension des habitats coralliens, ce qui permet de conclure qu’IB démontre une capacité de résilience, meme si la période étudiee reste trop courte pour pouvoir conclure définitvement. Les différentes trajectoires d'habitats observées ne peuvent pas être totalement interprétées sans combiner observations de télédétection et données in situ.