Mapping Corals, Algae, Seagrass and Substrata on Fringing Coral Reefs Using Synchronised Remotely Piloted Aircraft and Underwater Video at Vavanga Village, Kolombangara Island, Solomon Islands.

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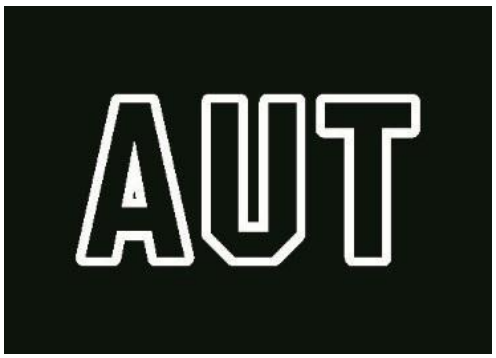

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Abstract

Fringing reefs are important ecological systems that support diverse marine life, fisheries and the livelihoods of coastal communities, particularly in large ocean states such as the Solomon Islands. Increasing disturbances, such as sedimentation, rising temperatures and coastal development and land use, have each heightened the vulnerability of fringing reefs to long-term degradation. To address these issues, accurate, repeatable assessments of reef condition and benthic community structure are necessary to monitor marine habitats and inform sustainable management.

This study assesses the effectiveness of georeferencing coral reef benthos and substrata in underwater video from synchronised Full Motion Video (FMV) acquired by a Remotely Piloted Aircraft (RPA). Nine-point overlays on still underwater video images were used to manually estimate percentage cover of benthic biota and substrata at 4,011 georeferenced point locations across and along the customary fringing reef of Vavanga, Kolombangara Island, Solomon Islands. Classification and regression trees (CART) were used to identify and map spatial predictors of benthic taxa and substrata in ArcGIS Pro and extracted underwater video frames were also analysed using the ReefCloud artificial intelligence classification software, which achieved moderate accuracy in broader classifications of coral and substrata.

Distinct patterns in benthic composition were observed across and along the reef and in relation to freshwater streams and lagoons. Macroalgae occurred across the shallow Vavanga reef flat, particularly *Padina,* with distinct bands of *Sargassum* and *Turbinaria ornata* on the mid to outer reef flat. South-east of the river, dense seagrass beds (*Thalassia hemprichii)* occurred on coarse sand across the inner to mid reef flat, while *Enhalus acoroides* occurred at the edge of the inner lagoon, further south. The inner reef flat north-west of the river at Vavanga was dominated by bare, weathered karst limestone, silt and fine sand, *Padina* and little or no seagrass or coral. This area may be influenced by the river, several small streams, mangroves, and another large inner lagoon. Small scattered, encrusting, and tightly branched hard corals (*Pocillopora verrucosa* and *P. meandrina*, *Acropora verweyi, Montipora digitata, Porites spp.)* increased from the mid to outer reef flat and crest, and coral cover rapidly increased with depth on the upper slope to approximately 30%. Finer-scale differences in coral cover and composition occurred along the coast to the north-west, at the river mouth at Vavanga, and in lagoons and creeks to the north and south of the village. The synchronised RPA-underwater video workflow demonstrates a repeatable, high-resolution method to map shallow marine environments. It provides a practical, spatially explicit tool to map fine-scale patterns in reef biota and morphology, and support community-based management in remote Pacific Island ecosystems.

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Firstly, I would like to acknowledge the people of Vavanga Village, Kolombangara Island, for enabling research within their reef environment. Their ongoing stewardship of the surrounding marine ecosystems emphasises the importance of understanding and protecting these vulnerable reef systems. I also acknowledge the broader *Connecting Coastal Communities* research initiative, whose collaborative work supports coastal monitoring and research across Pacific Island communities.

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Generative artificial intelligence tools (ChatGPT) and AI-assisted writing software (Grammarly) were occasionally used during the writing process to refine language and proofread. All research design, data analysis and interpretations presented in this thesis are the author's own work.

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed  ___

Name: Aidan Stockley

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List of abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
CART	Classification and regression tree (statistical method to model relationships and predict outcomes through explanatory variables)
CHAID	Chi-square Automatic Interaction Detection
DGPS	Differential global positioning system
DJI	Da-Jiang Innovations
EPSG	European Petroleum Survey Group coordinate reference system identifier (used to identify spatial reference systems)
Esri	Environmental Systems Research Institute
F1 Score	Statistical metric combining the precision and recall used to evaluate classification performance
FFmpeg	Open-source multimedia framework for extracting frames from videos.
FMV	Full Motion Video derived from RPA surveys
GIS	Geographic Information System
GPS	Global Positioning System
LIT	Line Intercept Transect
RPA	Remotely Piloted Aircraft
OBIA	Object-Based Image Analysis
PIT	Point Intercept Transect
PPV	Positive Predictive Value

ROS	Reactive oxygen Species linked with responses to coral bleaching stress
RTK	Real Time Kinematic
SPSS	Statistical Package for the Social Sciences
TNR	True Negative Rate
TPR	True Positive Rate
UAV	Unmanned Aerial Vehicle
VLC	VideoLAN Client
WGS884	World Geodetic System (global coordinate reference framework)

Ethics Statement

Research performed in this thesis involved non-invasive ecological surveys of coral reef habitats. No animals were disturbed, collected, or harmed during the study. All fieldwork was undertaken with the permission of local authorities and in cooperation with the Vavanga Village community.

1 Introduction

Coral reefs are major components of the global marine environment and span tropical and subtropical regions of the Pacific, Atlantic, and Indian Oceans (Moberg & Folke, 1999). These regions are characterised by warm temperatures and sufficient light to support the accretion of coral reefs and sustain a diverse array of marine life (Crabbe, 2008). Despite covering only 0.2% of the ocean, coral reefs host over 25% of marine species, highlighting their ecological and environmental importance *(*Coker et al., 2013; Crossland et al., 1991*).*

Fringing reefs are among the most common coral reefs globally (Blanchon et al., 2014) and are characterised by their proximity to the shores of high islands and continents. Fringing reefs can create a sheltered habitat for many species, protect the coast from waves, and are readily accessible by humans, but are highly vulnerable to their activities and terrestrial and freshwater influences *(*Juhasz et al., 2010*).* These reefs have a wide distribution between approximately 30° north and 30° south of the equator along the coasts of the Caribbean, the Bahamas, Australia, the Indian Ocean, West Africa, the Red Sea, Southeast Asia, and the Pacific from Australia and Japan to Panama (Carballo et al., 2019*).*
Fringing reefs have been described as having relatively distinct ecological zones, mainly in response to depth, light, and wave action, but also showing less apparent patterns in distribution related to freshwater input, disturbance, and differences in species composition (Figure 1*)*. The reef flat, the shallowest zone, may be sheltered enough to support algae and seagrass, but macro-organism cover may be low due to exposure during low tides, high temperatures, storms, heavy rainfall, and impacts of human activities. The reef crest is more elevated and absorbs high levels of wave energy, while supporting the most resilient coral species and coralline algae adapted to high hydrodynamic forces. The sloping fore reef has high coral cover and diversity at depths where there is some shelter from ocean swells but sufficient light for photosynthesis *(*Osorio-Cano et al., 2019; Shen et al., 2013*)*. The structural differences among the three zones shape patterns of biodiversity, ecological resilience, human impacts and their monitoring and management, with many nations boasting vast fringing reef systems *(*Carlson et al., 2019).

Figure 1. Generalised coral reef zonation diagram, USGS (2002).

The Solomon Islands are located in the Coral Triangle and include some of the world's most diverse and abundant marine ecosystems, including 485 coral species and more than 1,000 reef fish species *(*Jupiter et al., 2018*)*. Fringing reefs dominate this region, providing over 3,500 km² of habitat for framework-building coral species such as *Porites* and *Acropora*. Through their ability to dissipate strong waves and currents, these corals buffer coastlines and support high levels of biodiversity (Coral Triangle Initiative, 2014; Denley et al., 2020*)*.

These ecosystems are closely linked to Solomon Islands' coastal communities. Over 80% of the total population resides in coastal villages and depend on the resources fringing reefs provide *(*Schwarz et al., 2011*)*. Fisheries support small-scale income, provide stable subsistence, and contribute to food security. Without these benefits, Solomon Islanders would face harsh challenges, including poverty and potential displacement (Cohen et al., 2015; Rabbitt et al., 2019*).*

Local and global impacts put increasing pressure on vulnerable fringing reefs. Major threats include runoff from development, agriculture and forestry along coasts and catchments, unsustainable fishing, bleaching, ocean acidification and pollution (Speers et al., 2016; Zaneveld et al., 2016*)*. Increased sea surface temperatures and coral bleaching events have

led to habitat loss and significantly reduced the resilience of reef structures (Obura, 2005*)*. With such reefs located directly along shorelines, they are especially vulnerable to land-based pressures such as sedimentation and coastal development. Mitigating these pressures on reef systems is crucial to developing effective strategies to prevent further harm *(*Ensor et al., 2017*)*.

Adaptive management to understand impacts and the effectiveness of their management requires long-term monitoring of trends in coral reef abundance and diversity in relation to environmental conditions and processes. Long-term, consistent monitoring enables scientists working with local communities to detect early warning signs of stress on fringing reefs, most notably bleaching events and shifts in species composition (Alexander et al., 2019; Obura et al., 2019*)*. The need to monitor change is increasingly significant due to the added pressures of climate change and rising temperatures *(*Harvey et al., 2018*)*.

Research on fringing reefs, especially adjacent to river mouths, is under-represented in high-resolution spatial mapping studies, particularly in the Solomon Islands *(*Lutzenkirchen et al., 2024*).* These environments experience intense land-sea interactions, heightened thermal stress, and sediment loading (Comfort et al., 2019*)*. Despite these threats, these locations are often excluded from long-term monitoring, with more effort directed toward lagoons and fore reefs. As a result, fine-scale variability in benthic composition on fringing reefs and the influence of local environmental gradients remain poorly measured *(*Lutzenkirchen et al., 2024; Zweifler et al., 2021).

This study aims to address this gap by mapping and assessing reef condition and benthic composition over the fringing reef of Vavanga Village, Kolombangara Island, Solomon Islands. It integrates Full Motion Video from drones synchronised with underwater video surveys, to provide a high-resolution, repeatable, spatial assessment of the distribution of species and substrata *(*Piazzolla et al., 2024; Hodgson et al., 2013*)*.

It builds on prior research by Grace Martin, who investigated the reef to the south-east of the river at Vavanga. This study seeks to extend spatial coverage by combining and modelling spatial patterns from Martin's study with those from this study for the north-western side of the river. It aims to improve our spatial understanding of reef flat ecosystems while developing innovative monitoring methods to support community-based management in the Solomon Islands and elsewhere *(*Wenger et al., 2020*)*.

1.1 Aim

The aim of this thesis is to spatially map and assess the ecological condition of the northern fringing reef located at Vavanga Village, Kolombangara Island, Western Province, Solomon Islands. It builds on prior research conducted by MSc graduate Grace Martin, who studied the island's southern fringing reef. This study extends spatial monitoring to the adjacent reef as a baseline for customary management and to help understand relationships between benthic biodiversity and environmental drivers at broader spatial scales. The Solomon Islands remain underrepresented in existing studies on high-resolution fringing reef monitoring. This research seeks to strengthen baseline ecological data and to help develop and trial new techniques for spatially referencing and modelling underwater survey data.

1.2 Thesis Structure

Following this chapter, Chapter 2 explores the ecological, methodological, and socio-economic literature relevant to fringing reefs and benthic surveys. Chapter 3 introduces the study location at Vavanga and the methods, including the use of Remotely Piloted Aircraft (RPA, or drone), Full Motion Video (FMV), integration of underwater imagery, classification steps, and analyses. Chapter 4 presents spatial and statistical results. Chapter 5 discusses ecological patterns, methodological implications, and the relevance of monitoring in a broader socio-ecological context. Chapter 6 summarises the key findings and outlines recommendations for future research and reef management.

1.3 Research Questions

This study aims to address the following research questions:

1. How effective is an integrated RPA Full Motion Video and synchronised underwater imagery workflow for mapping benthic habitats and species on fringing reefs?
2. What spatial patterns in benthic composition, diversity and substrata structure occur along environmental gradients at Vavanga?
3. To what extent do hydrodynamic exposure and fluvial proximity influence benthic zonation across the fringing reef?

2 Literature Review

2.1 Ecological significance of fringing reefs

2.1.1 Reef structural foundations and trophic function

Fringing reefs are among the most ecologically significant marine ecosystems globally because of their structural complexity and biological diversity. Reef foundations are comprised of calcium carbonate ($CaCO_3$), which hardens as coral polyps attach to rock substrata along coastlines (Glynn & Manzello, 2015; Moberg & Folke, 1999*).* The growth of fringing reefs is driven by the mutualistic relationship between corals and their symbiotic zooxanthellae, microscopic algae that live within coral tissue. In exchange for sunlight and protection, zooxanthellae provide their host coral with photosynthetically derived organic carbon (photosynthate) and oxygen, enabling a photosynthetic relationship that fuels accelerated calcification and drives rapid reef formation, supporting abundant marine life (Hatcher, 1984; Wild et al., 2004). This tight pairing between primary production and calcification processes supports reef accretion and the three-dimensional structure that underpins high biodiversity.

These reefs are diverse ecosystems that support a wide range of marine organisms and complex biotic interactions. Mesopredators such as reef sharks and groupers regulate trophic dynamics by controlling populations of small fish, molluscs, and crustaceans through predation (Sandin et al., 2008). These prey species support trophic transfer by grazing on algae and maintaining space for coral recruitment, thereby reinforcing healthy nutrient cycling. While trophic interactions are well documented in the Central Indo-Pacific and Caribbean regions, remote reef systems in Melanesia, including those in the Solomon Islands, are less represented in monitoring and modelling efforts than major, well-researched reef systems (Norström et al., 2008*).*

A healthy balance is essential to maintaining ecosystem stability. The removal of predators can destabilise the trophic structure, triggering significant shifts in community composition, while the loss of herbivores can lead to algal overgrowth, oxygen depletion, and coral stress. In systems where fishing pressures have already altered predator-prey relationships, trophic imbalances can emerge well before any visible signs of reef collapse (Darling et al., 2017; Graham & Nash, 2012). This highlights the importance of monitoring both structural condition and ecological function, particularly in subsistence-dependent communities.

Another key function of fringing reefs is their role as refuge habitats for vulnerable marine life. Species such as fusiliers (*Caesionidae*) rely on the strength and structural complexity of fringing reefs for protection, using coral outcrops to avoid predation. By providing structurally complex habitats and abundant benthic algal resources, fringing reefs enable herbivorous species to forage safely while reducing exposure to predation (Komyakova et al., 2018; Almany, 2004). These species would be far more vulnerable in the open ocean, facing significant predation risks without shelter. With reef structure degraded, vulnerable species are threatened, which, in turn, can have cascading effects on fisheries, other organisms, ecological processes, and stable states *(*Jones & Syms, 1998*)*.

A key contribution of fringing reefs is to maintain healthy nutrient cycles. These systems exhibit remarkably efficient internal recycling despite usually occurring in oligotrophic waters. In warm tropical waters, both phytoplankton productivity and limited nutrient availability are typically low *(*Hatcher, 1984; Wild et al., 2004). However, their proximity to shorelines enables land-based nutrients to facilitate a stronger food web, resulting in a diverse energy flow (Garren & Azam, 2012*).* Understanding this nutrient-cycling function is crucial to sustaining productivity in Pacific Island fisheries, where reef dependence is among the highest.

2.1.2 Coral morphology and cross-reef zonation

Branching coral species, particularly *Acropora* and *Pocillopora*, are vital components of Indo-Pacific reef systems that help shape reef structural complexity. Their fine-scale branching morphology provides essential habitat for juvenile fish and invertebrates, thereby increasing biodiversity and trophic connectivity *(*Beukers & Jones, 1998). Despite their ecological importance, these taxa are highly sensitive to sedimentation and thermal stress due to their delicate skeletal structures and high surface-area-to-volume ratios (Bonin, 2011; Darling et al., 2017*).* The distribution of branching corals is closely linked to environmental gradients, particularly hydrodynamic exposure and sediment retention across reef systems. Their rapid growth and contribution to carbonate production make these species vital for ecosystem function and recovery.

In contrast to branching species, massive corals such as *Porites* boulder corals display hemispherical growth forms and dense skeletal structures, which enhance their resistance to wave energy and sedimentation (Done & Potts, 1992*)*. Their morphology enables *Porites*

colonies to persist under a variety of conditions, occupying the reef flat, crest and fore reef zones. Foliose and encrusting genera such as *Montipora* occur under a range of reef environments and have a moderate tolerance to hydrodynamic conditions (Evensen et al., 2015*).* Representative species include branching forms, such as *Montipora digitata* and foliose or whorled forms such as *M. aequituberculata,* which are commonly associated with reef-flat and crest environments in Indo-Pacific reef systems. The morphological differences among coral taxa underpin cross-reef structure, reinforcing the importance of physical energy gradients and sediment retention in shaping reef-flat zonation patterns across Indo-Pacific reef systems *(*Done, 1982; Huang et al., 2014).

Due to their exposure to thermal and hydrodynamic variability, reef flats strongly differ from the reef crest and fore reef environments. During low tides, shallow reef flats can experience higher temperatures and prolonged exposure to air, creating physiologically stressful conditions for corals and associated biota **(**Jokiel & Coles, 1990***).*** Encrusting and massive species may exhibit greater tolerance to thermal and sedimentary stress, but branching and foliose corals are often more vulnerable to fluctuations in sedimentation, temperature, and water exchange **(**Darling et al., 2017**).** As a result, reef flats often display spatially heterogeneous coral assemblages, shaped by both environmental exposure and species-specific stress tolerances. Together, these ecological gradients provide a structural framework for interpreting benthic assemblages on fringing reef flats, particularly in environments influenced by hydrodynamic exposure and river-derived sediment inputs.

2.1.3 Associated benthic communities: seagrass and macroalgae

In addition to coral assemblages, nearshore reef systems frequently support seagrass meadows, which contribute to sediment stabilisation, nutrient cycling, and habitat for marine invertebrates and juvenile fishes (Duarte, 2002; Orth et al., 2006*).* Seagrass distribution is significantly influenced by hydrodynamic exposure and light availability, with optimal conditions for seagrass occurring in low-energy environments (Waycott et al., 2009*).* Physical gradients across fringing reefs therefore influence not only coral assemblages, but also seagrass distribution.

Macroalgal assemblages are an integral component of coral reefs. Both fleshy brown and turf macroalgae contribute to primary productivity, food webs and habitat. Coralline algae cement and consolidate the reef crest, coral rubble and calcium carbonate from many

different organisms, including corals, *Halimeda*, foraminiferans, molluscs and echinoderms. *Halimeda* is a calcifying green alga that significantly contributes to carbonate sediment production. Fleshy brown genera include *Padina*, *Sargassum* and *Turbinaria ornata*, all of which are associated with relatively exposed or sediment-influenced reef flats (Hillis-Colinvaux, 1980; Littler & Littler, 1984; Stiger & Payri, 1999; Hoey & Bellwood, 2009*).* The abundance of each genus is notably influenced by light availability, substrate stability, and sediment accumulation. Fleshy brown macroalgae increase rapidly in transitional reef-flat environments with reduced coral cover and sufficient substrate stability (McCook, 1999; Fabricius, 2004*).*

Macroalgal distributions across fringing reefs provide insight into the effects of coastal land use, fisheries, global warming and management. Macroalgae and filamentous algae can compete with coral colonies for space, light and nutrition, particularly under conditions of increased nutrient input (McCook, 1999; Hughes et al., 2007*).* Macroalgal communities across fringing reefs are commonly structured by hydrodynamic exposure and sediment dynamics, with benthic composition shifting along cross-reef gradients in response to water movement (Fabricius, 2004; Storlazzi et al., 2011*).* Patterns of macroalgal dominance reflect the changing condition of fringing reefs and can serve as an early indicator of potential phase shifts from coral- to macroalgae-dominated reefs (Hughes, 1994).

2.2 Climate and environmental stressors

2.2.1 Climate change and coral bleaching

Climate change has emerged as the most significant large-scale threat to coral reef systems globally. Rising temperatures, ocean acidification, and increasing thermal anomalies place increasing pressure on fringing reef environments (Hoegh-Guldberg et al., 2007; Speers et al., 2016*)*. As surface temperatures rise and frequent bleaching events occur, reefs experience habitat loss and reduced structural complexity. Due to their proximity to shorelines, fringing reefs are also vulnerable to land-based stressors, which can compound thermal impacts. By mitigating these pressures, effective strategies can be developed to help prevent further harm *(*Edinger et al., 1998*)*.

As sea surface temperatures continue to increase, pressures on fringing reef systems further intensify. Increases in sea surface temperatures of ~1-2°C above seasonal maxima can

trigger coral bleaching. When ocean temperatures exceed 32°C, zooxanthellae produce reactive oxygen species (ROS), resulting in oxidative stress (Szabó et al., 2020). The coral's stress response is to forcefully expel the zooxanthellae from their skeletons, resulting in bleaching and potentially death *(*De'ath et al., 2009; Vidal-Dupiol et al., 2009*).* These increased temperatures have driven a significant rise in mass bleaching, with a major surge over the past 30 years causing widespread coral reef mortality (Heron et al., 2016*).* Recurrent thermal anomalies have rapidly reshaped coral reef assemblages at regional scales, leading to long-term declines in structurally complex, fast-growing coral taxa (Hughes et al., 2017; Hughes et al., 2018*).*

Coral bleaching has been documented extensively over the past six decades but long-term monitoring efforts to combat climate change are predominantly focused on large barrier reef systems (Rivera-Sosa et al., 2025*).* The Great Barrier Reef in Australia and Moorea in French Polynesia have received sustained scientific attention due to their size, accessibility, and ongoing support from established research institutions (Mellin et al., 2020). In contrast, fringing reefs, despite being the most abundant reef type globally, are significantly underrepresented in long-term bleaching datasets. Fringing reefs are especially prevalent in developing nations across the Pacific and Indian Oceans, where they play a key role in ecological and coastal protection (Moffitt & Kumar, 2017).

This disparity is exacerbated by logistical challenges and limited infrastructure, which hinders the monitoring of extensive fringing reefs. This has contributed to a lack of standardised protocols and inconsistent methodologies, complicating analyses of long-term data. The impacts of bleaching on fringing reef systems are, therefore, often captured only in short-term studies, making it difficult to track long-term climate impacts (Obura et al., 2019; Rivera-Sosa et al., 2025*).*

Recent research in the Solomon Islands reveals that bleaching impacts are not spatially uniform, with substantial sub-regional variation observed across the Western Province. Among these reef systems, bleaching responses were heterogeneous, reflecting localised differences in both exposure and hydrodynamics (Denley et al. 2020**)**. These findings strongly align with prior assessments documented in the Status of Coral Reefs in the Southwest Pacific (Lovell et al., 2004*),* which demonstrated pronounced variability in coral conditions across various Melanesian reef systems. This spatial heterogeneity reflects the need for fine-scale, site-specific monitoring approaches capable of detecting early signs of

bleaching, especially on shallow fringing reefs that experience periods of amplified thermal variability.

2.2.2 Sedimentation and land-based stressors

Fringing reefs are highly susceptible to land-based activities, including logging, agriculture, and coastal development (Carlson et al., 2019; Jupiter et al., 2018). These practices accelerate catchment erosion, increasing terrestrial runoff of sediment and organic matter into nearby reef systems. The resulting influx of sediments and organic matter reduces water clarity, blocks sunlight for photosynthesis, and smothers coral polyps, greatly impacting coral reef community structure *(*Fabricius, 2004; Golbuu et al., 2007*).* These factors inhibit coral growth and minimise reef resilience (Fabricius & De'ath, 2000; Wolanski et al., 2004*).*

Additionally, heavy sedimentation disrupts coral recruitment by obstructing larval settlement and smothering crustose coralline algae, a crucial surface for juvenile coral development. Over time, this results in declines in coral cover, reduced structural complexity, and lower abundance in herbivorous fish populations (Fabricius, 2004). Regions such as the Roviana Lagoon are experiencing substantial impacts, as persistent sediment runoff from agricultural activities has resulted in severe coral degradation. Stress from sedimentation acts as a chronic ecological pressure, limiting reef regeneration and compounding other stressors, including warming and acidification (Aswani, 2014).

Despite sedimentation's threat as a stressor to coral reefs, coral responses to increased turbidity are highly context-dependent and influenced by local environmental factors. Past studies have shown that various coral assemblages can persist in naturally turbid environments, particularly when sediment exposure is persistent and light attenuation remains within tolerable limits *(*Albert et al., 2015a*)***.** These systems, however, remain exceedingly sensitive to periodic increases in sediment delivery, a common attribute of river mouths that experience intense rainfall and periods of high river discharge, which can rapidly exceed the tolerance threshold of susceptible corals.

Beyond catchment-derived inputs, cross-reef hydrodynamic gradients play a major role in sediment redistributions across shallow reef flats. As reef crests dissipate incoming wave energy, distinct zones of energy attenuation form, which influence patterns of sediment

deposition and resuspension (Storlazzi et al., 2011*).* Within shallow reef-flat environments, wave-driven processes can mobilise coarse rubble in high-energy crest zones, while promoting fine sediment accumulation in sheltered reef flats (Ogston et al., 2004). As a result, substrate composition across fringing reefs is structured by both river input and cross-reef energy gradients, which regulate sediment transport.

In Marovo Lagoon, reduced logging pressures and improvements in catchment management enabled more effective coral recovery efforts, emphasising the critical role of land-based governance in regulating sediment delivery and enhancing reef resilience (Jupiter et al., 2018**).** These findings suggest that reef flats directly adjacent to river mouths are most likely to exceed sediment tolerance thresholds, with impacts often amplified on volcanic islands. Steep catchments and high rainfall characterise these zones, a trend observed throughout the Solomon Islands.

In a tropical environment with high rainfall, river plume dynamics in the Solomon Islands greatly intensify sediment exposure on nearshore reef flats. Kolombangara (Figure 2*)*, a volcanic island, features steep catchments that rapidly transport silt and mud into adjacent reef systems during wet events, amplified by high rainfall (Morrisey et al., 2003*)*. These sediment plumes significantly reduce water clarity and smother benthic communities with fine sediments, suppressing photosynthesis and hindering available nutrients. Therefore, reef flats adjacent to river mouths are subject to increased stress from periodic sediment loading and persistent turbidity. This combination has made these reefs highly vulnerable to degradation and intensified impacts on land-sea connectivity (Hairsine, 2017).

Figure 2. Location of Kolombangara Island within the Solomon Islands, Weeks et al., 2017.

2.3 Socio-economic pressures on reef health

Beyond ecological processes, fringing reefs provide Pacific Island communities with a wide range of services that support food security and income diversification. Reef-associated resources play a critical role in sustaining livelihoods in regions where alternative food sources and economic opportunities are limited (Albert et al., 2015b*).* These services are vital in remote coastal communities, where daily subsistence and small-scale income are directly tied to reef health.

The impact fringing reefs have on small-scale fisheries and local food systems cannot be understated. Pacific nations rely heavily on subsistence fishing, offering readily accessible sources of both protein and income. In regions of the Solomon Islands, such as the Roviana and Vonavona lagoons, many coastal communities rely almost entirely on reef-based fisheries for their dietary protein. Nationally, seafood consumption averages 73 kilograms per capita annually, with fish accounting for approximately 94% of all animal-source protein intake (Dey et al., 2016; Farmery et al., 2020). In contrast, the global average for seafood

consumption is only 20 kilograms per person, underscoring the region's crucial nutritional dependence on reef-based fisheries (Tilley et al., 2019).

Fringing reefs also play an essential role in the socioeconomics of the Solomon Islands and other Pacific nations. Fringing reefs contribute to both tourism revenue and fisheries production *(*Aswani, 2014*)*. Although still relatively small compared to countries such as Fiji and Vanuatu, the Solomon Islands has the potential to generate substantial income through environmental tourism. With exceptional diversity and various reefs in favourable condition, the marine habitat attracts divers, snorkelers, and scientists, all of whom contribute to local incomes *(*Diedrich & Aswani, 2016; Lovell et al., 2004*).*

However, tourism growth in Solomon Islands waters also introduces ecological risks, specifically where activities are poorly regulated. Activities such as unregulated diving, snorkelling and boat tours can lead to direct habitat damage, while contributing to localised overfishing pressures. (Diedrich & Aswani, 2016). These impacts degrade the long-term resilience of coral ecosystems, as gradual damage from coral harvesting and recreational overuse threatens the stability of resources on which local communities rely (Morrison, 2012). Prioritising the maintenance and structural integrity of fringing reefs across the Coral Triangle is therefore essential to ensuring livelihoods from tourism-based economies can thrive while preserving biodiversity (White et al., 2014).

Socioeconomic factors often exacerbate sedimentation's impacts, creating feedback loops that further degrade fringing reefs. Coastal communities dependent on reef-based resources for income and nutrition face intensified pressures as reef health declines. Overharvesting herbivorous fish disrupts the coral-algal balance, leading to further ecological decline (Teh et al., 2013; Cinner et al., 2012*).* This reduction in grazing pressure introduces competitive shifts, facilitating the growth of fast-growing algae, while weakening reef structural complexity and long-term productivity.

A lack of environmental regulations and watershed management has exacerbated land-based runoff, which remains largely unchecked in parts of the Solomon Islands. Wenger et al. (2020) demonstrated that even optimal forest management could not entirely prevent sediment delivery to adjacent reef systems. In low-clearing scenarios, up to 32% of the reefs remained exposed to elevated sedimentation. In unmanaged catchments, sediment runoff

placed up to 89% of nearby reefs at risk, including ecosystems surrounding Kolombangara Island. These findings underscore the urgent need for integrated land-sea governance to halt further reef decline while reducing socio-economic vulnerability in communities that depend on reef-based resources.

This interconnection between reef condition and community livelihoods highlights socio-economic vulnerabilities in reef-dependent systems. This underscores the importance of locally relevant, targeted conservation and spatial monitoring approaches. Throughout the Solomon Islands, where access to reef environments and stewardship are embedded within customary marine tenure systems, effective management must integrate ecological assessment with locally grounded governance foundations.

2.4 Customary knowledge and Indigenous management

2.4.1 Tabu zones and customary marine tenure

The critical role of Indigenous knowledge in sustaining fringing reefs spans the entire Pacific region and beyond (Aswani & Hamilton, 2004). Traditionally, chiefs hold authority over land and sea, particularly reefs, with their initial decisions often dictated by established customary practices. Historically, frameworks based on tabu (no-take) zones are deeply embedded in the nation's history, enabling stronger reef resilience and fish stock recovery (Cohen et al., 2015). As these methods align with modern goals of restorative conservation, scientists and indigenous communities often work closely together to promote effective reef management (Cinner & Aswani, 2007*)*.

Adaptive local responses to environmental change are shaped by ethnobiological knowledge and long-standing relationships with reef ecosystems. In the Solomon Islands, livelihood resilience is closely tied to Indigenous knowledge, which informs adaptive decision-making and traditional fishing practices. Declines in reef health can therefore trigger cascading socio-economic consequences that extend beyond ecological degradation alone, reinforcing the importance of spatially explicit monitoring approaches to inform locally relevant management strategies (Aswani, 2014*).*

In regions such as Roviana and Vonavona, clan-based ownership is standard, with these rights passed down through generations. Traditional tabu practices have shown increased biomass and improved overall reef health when paired with community-based enforcement and local ecological knowledge (Ramenzoni, 2021*).* External conservation strategies, however, tend to fail when these management systems are ignored, as the knowledge indigenous communities provide is crucial to the persistent maintenance of reefs (Foale & Manele, 2004).

2.4.2 Blending scientific and cultural approaches

Evidence suggests that conservation strategies based solely on external scientific frameworks, without community engagement, often fail to achieve long-term success and lack local legitimacy. Cinner and Aswani (2007) highlight that efforts imposed without formal recognition of customary marine tenure are often ignored or resisted, underscoring the need for co-management models that respect the governance systems of Indigenous peoples.

By incorporating Indigenous and Western approaches, reef management can thrive while respecting cultural sovereignty. As customary owners of reef environments, local communities possess essential knowledge of tenure boundaries, ecological indicators, and ethical fishing practices. When combined with remote sensing and reef surveys, which provide accurate readings on coral reef health, the Solomon Islands provides a strong case study demonstrating the effective integration of Indigenous governance systems with scientific reef monitoring practices (Muller et al., 2019).

One such mechanism, participatory mapping, has emerged as an effective tool for integrating Indigenous knowledge with scientific monitoring, particularly in remote regions with limited datasets. Community-led mapping near Boe Boe, Solomon Islands, enhanced spatial understanding of reef use and reinforced local stewardship through participatory mapping (Piccolella, 2013*)*. The ‘Ridges to Reef’ programme in Choiseul, Solomon Islands, also demonstrated how co-produced spatial datasets can help improve conservation and management outcomes in remote regions (Kereseka, 2014). Both examples underscore the need for collaborative monitoring and repeatable spatial data that align with marine tenure systems, values and practices.

2.5 Reef monitoring techniques

2.5.1 Diver-based monitoring methods

Coral reef monitoring has historically relied on in situ, diver-based transect and quadrat techniques. Notable forms include Line Intercept Transect (LIT), Point Intercept Transect (PIT), and belt quadrats. Each of these methods can produce quantitative estimates of benthic composition, coral cover, and species abundance. These methods are commonly used in conjunction with Indo-Pacific ecological monitoring and remain the standardised approach across various long-term initiatives (English et al., 1997; Hill & Wilkinson, 2004*).*

These methods, however, are labour-intensive and limited in coverage, while being subject to issues such as observer bias. Completing a LIT or PIT transect over 50 meters in length can take over an hour underwater, severely limiting data collection in a single day. An additional issue, observer bias, is a further problem surveys face. Two divers may record different cover estimates for the same fine-scale features, such as algal turf or partial mortality (Buckland et al., 2009; Facon et al., 2015).

Belt quadrats deliver excellent detail at a finer scale; however, they struggle to capture the overall variability of whole reefs when compared with remote sensing approaches (Palma et al., 2017*)*. These limitations are especially apparent at remote sites, where a lack of diving infrastructure and higher costs can hinder efficient survey efforts (Mumby et al., 2003*).*

Despite these limitations, traditional in situ survey methods remain crucial for reef health assessment, enabling early detection of reef degradation and prompt management responses. PIT, belt transects, and photo quadrats each provide critical biological data, showcasing important habitat and environmental characteristics that help assess reef health **(**Page et al., 2016*)***.** Despite this, logistical challenges persist. Diver safety and depth limitations both continue to restrict an efficient approach to larger-scale reef monitoring efforts.

Underwater photography and video recordings of reef habitats have been used since the early 1990s to routinely monitor changes in coral cover, for example, through the Australian Institute of Marine Science Long Term Monitoring program on the Great Barrier Reef (Sweatman et al. 2011), as well as to assess the impacts of offshore tourism platforms.

Snorkellers on underwater scooters equipped with video are used in this study to capture multiple images of reef biota at distances of up to a metre. However, georeferencing the locations of these underwater images is not straightforward, as GPS signals do not travel through water. This study is relatively novel in that underwater images are georeferenced from synchronised imagery acquired by a drone equipped with Full Motion Video (FMV), which continuously embeds drone navigation and camera data into aerial video recordings. Georeferencing underwater images and observations can be used to enhance habitat classification of drone-captured aerial photomosaics *(*González-Rivero et al., 2020*)* and, as trialled here, to interpolate species and habitat distributions and, in the future, to measure change.

2.5.2 Emerging remote sensing tools

Advancements in remote sensing have been increasingly applied in reef research. Remotely Piloted Aircraft (RPAs) can capture high-resolution aerial imagery, particularly well-suited for mapping coral reefs over broad areas at an affordable cost *(*Collin et al., 2019; Murfitt et al., 2017**).** Compared to satellite imagery, RPAs offer centimetre-scale resolution (vs metre-scale) and can be used flexibly at different sites and times. This provides a significant improvement in spatial and temporal resolution, enabling more targeted surveys. (Klemas, 2015; Casella et al., 2017*).*

When combined with GIS software, RPAs enable researchers to develop maps of habitats and species distributions. Image-based reef mapping incorporates object-based image analysis (OBIA), Artificial Intelligence, statistical models and training data to improve classification accuracy. At Heron Reef on the Great Barrier Reef, Roelfsema et al. *(*2018*)* used semi-automated OBIA workflows to improve classification consistency and spatial detail. Additional studies refining protocols for expert-led training emphasised the role of high-quality reference data as a baseline (Roelfsema et al., 2021). The Millennium Coral Reef Mapping Project, a larger-scale initiative, is another example of repeatable, standardised workflows that balance spatial coverage with reliability (Andréfouët & Bionaz, 2021).

2.5.3 Constraints and technical challenges

Despite offering numerous advantages, remote sensing technologies remain constrained by environmental factors that hinder their effectiveness and overall performance in dynamic reef environments *(*Mahrad et al., 2020). Various studies performed in tropical reef regions have

reported environmental conditions that reduce the overall quality and reliability of reef imaging.

Hedley et al. (2016) documented that sun glint, cloud cover, and wave-driven surface distortions each contribute to notable data loss and mapping inaccuracies during RPA capture. These limitations significantly reduce the reliability of long-term comparisons in studies, making it challenging to track reef changes over multiple years. This issue is further exacerbated in remote, high-priority areas with fewer resources.

Despite the value of underwater video recording methods, coverage remains limited by the time and depth at which divers can operate without risking injury. Operational depth and bottom-time limitations restrict spatial coverage, while prolonged exposure at greater depths of 30 meters introduces additional safety constraints. In addition, video quality is greatly diminished by environmental factors such as turbidity and low-light levels and is further affected by diver movement *(*Letessier et al., 2015*).*

Jones et al. (2021) showed that suspended sediments in turbid nearshore reefs towards the central Great Barrier Reef reduce underwater light intensity and significantly diminish the spectral quality. This results in significant loss of visibility and colour distortion in the video footage. These factors can limit the ability to record fine-scale benthic features and create new challenges when analysing coral cover. As a result, the most effective use of underwater video footage may be in combination with additional monitoring tools. By working alongside RPA surveys rather than as a standalone approach, reef environments can be mapped at a greater scale with greater spatial accuracy *(*Raoult et al., 2019*)*.

2.5.4 Integrating remote sensing with indigenous monitoring

In the Solomon Islands, the use of RPAs and underwater cameras has become increasingly relevant, particularly in the nation's vastly understudied reef environment (McKenzie et al., 2020). As a nation with resilient community-based monitoring systems that incorporate local tribes and customary governance structures, this partnership provides a strong foundation for enhanced reef monitoring, complemented by traditional knowledge and expertise. This partnership enables the development of inclusive, data-supported strategies to benefit conservation efforts and customary use (Lauer & Aswani, 2009). The integration of repeatable spatial monitoring tools combined with locally led stewardship provides a practical pathway for long-term reef-flat assessment across data-limited regions, such as

Kolombangara. This pairing highlights the need for approaches that combine scalable remote sensing practices with locally grounded governance.

2.6 Research gap and justification

2.6.1 Spatial gaps in current reef monitoring

Disregarding spatial dependence can lead to biased inference about ecological patterns, misidentification of environmental drivers, and reduced reliability of spatial predictions (Legendre, 1993). As a result, spatial point-based approaches and distance-based analyses have been widely adopted for quantifying benthic variability while identifying underlying drivers (Andrew & Mapstone, 1987; Gatrell et al., 1996). Such frameworks are useful for investigating fringing reef adjacent to river mouths, where strong environmental gradients can operate over short spatial scales.

Despite the growing number of coral research studies performed since the 1990s, many fringing reefs, particularly those along coastlines of the Solomon Islands, remain incompletely mapped and under-monitored (Glynn, 2016*).* Numerous studies concentrate on accessible lagoon environments, with Roviana receiving the most attention, and most spatial assessments focus on the fore reef and lagoon environments. In contrast, shallow reef flats adjacent to river mouths receive less attention. Studies conducted in regions such as the Roviana Lagoon have provided datasets that provide valuable insights into reef condition; however, comparable spatial coverage remains lacking for exposed reef flats shaped by land-sea interactions (Aswani & Albert, 2015*)*. These understudied environments tend to experience some of the most intense pressure via sediment and thermal stress, yet remain poorly quantified (McLachlan et al., 2020*)*. This highlights a critical gap in current monitoring efforts, and this study aims to address this.

In addition to the limited spatial coverage, there remains a lack of studies that explicitly incorporate spatial modelling of benthic habitats and species on fringing reefs. Environmental gradients and spatial dependence can be quantified in a range of statistical and spatial models. For example, classification and regression tree (CART) analyses were used to map cross-shelf and along-shelf patterns in species composition for soft and hard coral, fish, seagrass, and algal data sets for the Great Barrier Reef World Heritage Area. These are useful for exploring nonlinear relationships and threshold responses to environmental change, such as proximity to the reef crest and riverine inputs *(*De'ath & Fabricius, 2000).

In some areas, long-term ecological and management programs, such as customary marine tenure systems and enforced no-take zones, are practised by local communities (Aswani, 2014*).* Such programs support reef resilience and the recovery of fish stocks across the Solomon Islands. Areas such as Baraulu village and Saikile observed a 3-to 5-fold increase in fish biomass, and a significant boost in key reef species, including humphead parrotfish (*Bolbometopon muricatum*), compared to areas that experienced increased fishing numbers (Aswani & Hamilton, 2004; Cinner & Aswani, 2007).

2.6.2 Kolombangara Island and Vavanga

Although fish surveys have been conducted at Kolombangara, very few spatial drone-based studies exist, particularly in the vicinity of Vavanga Village (Sabetian, 2003). This study aims to address this gap using RPA technology to map fringing north and south of the river at Vavanga. This approach, which works in tandem with synchronised underwater video, captures fine-scale variability in coral cover and provides a high-resolution view of coral composition. When combined with ground-truthing data, this method provides a repeatable, detailed baseline for long-term monitoring (Teague et al., 2022).

While machine learning and semi-automated classification tools have seen rapid advances in reef research, their implementation in Pacific Island contexts remains limited. AI-assisted classification provides opportunities to enhance the speed and reliability of image classification. Platforms such as ReefCloud enable evaluation of observer consistency and semi-automated training to automate recognition of life forms and habitats from underwater imagery. The incorporation of such tools enhances confidence in benthic estimates and significantly contributes to the development of repeatable monitoring workflows, optimised for remote reef systems (González-Rivero et al., 2020).

2.6.3 Cultural integration and Vision Mātauranga

While this field research is entirely situated in the Solomon Islands, it is conducted within a New Zealand academic context, where frameworks such as Vision Mātauranga shape expectations for Indigenous partnership and collaborative research practice (Ministry of Research, Science and Technology, 2007*).* While unique to New Zealand, its values of recognising Indigenous knowledge and collaborative governance strongly align with those of communities in Solomon Islands and their approach to reef management (Teariki & Leau, 2023).

Research in the Western Pacific has shown that collaboration between scientists and local communities enhances the effectiveness of conservation outcomes (Lauer & Aswani, 2009). By approaching reef research in the Solomon Islands with respect for Indigenous ecological knowledge, long-term health and suitable reef stewardship are strengthened. Ultimately, this study aims to reflect these principles through an integration of scientific methods and grounded knowledge. The following chapter outlines specific methods and workflows developed to help address these principles.

3 Methods

3.1 Study area and survey design

This thesis focused initially on the fringing reef to the north-west of the river at Vavanga, Kolombangara Island, Solomon Islands (Figure *3*), but then incorporated data from a previous study south-west of the river into an overall model of these sections of the customary area. The village of Vavanga is located on the island's south-western coast at approximately 8°03'40.8"S 156° 58' 07.5"E. The northern fringing reef extends laterally along the coastline, north of the river mouth in Vavanga, and offshore to the shallow outer reef flat, crest and upper reef slope. This forms a primarily shallow, fringing reef system, strongly influenced by land-sea interactions, particularly the influx of sediment from neighbouring catchments.

Figure 3**.** Overview of the north and south survey locations, Vavanga Village, Kolombangara, Solomon Islands, Martin, 2024

Field surveys were carried out on site between the 4th and 15th of December 2022. During this period, multiple RPA flights and underwater video transects were conducted daily. This study analyses drone and underwater video collected in a previous study by Martin (2024). Figure 4 and Figure *5* summarise the full process from data acquisition through to benthic

classification and subsequent analysis. Figure 4 outlines the workflow integrating drone-derived FMV with synchronised underwater imagery to produce frame-based benthic data and percentage cover estimates. Figure 5 displays the analyses applied to the classified benthic data, showing an analytical pathway trialling AI recognition of benthic organisms and substrata and another involving manual classification of images and interpolating the spatial distributions of benthic organisms and substrata.

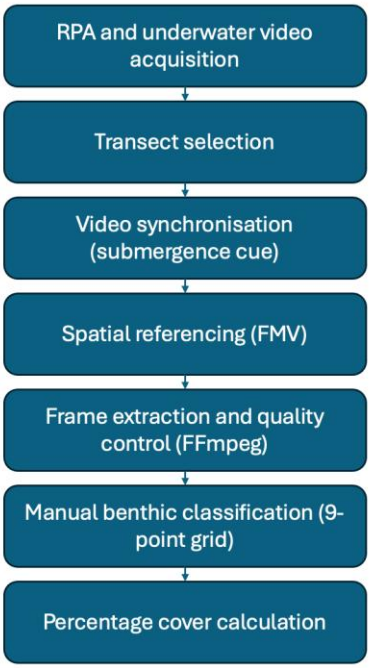

Figure 4. Overview of the workflow used to produce benthic classification data through integrated RPA and underwater video surveys. The workflow demonstrates the order used to generate the dataset, from data acquisition and video synchronisation to spatial referencing using Full Motion Video (FMV), frame extraction and quality control, manual benthic classification using a nine-point grid overlay, and calculation of percentage cover.

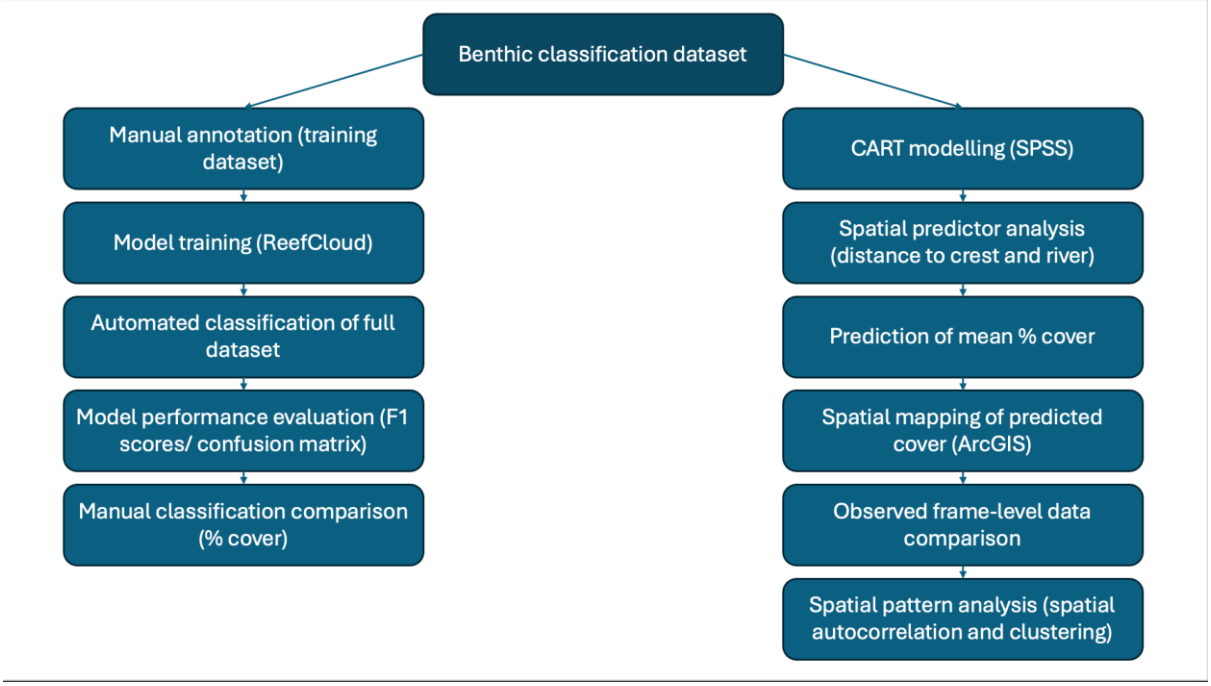

Figure 5. Analytical framework applied to the benthic classification dataset. On the left is a machine learning approach using ReefCloud for model training, automated classification, and performance evaluation of benthic image classifications. On the right, statistical modelling using CHAID (Chi-squared Automatic Interaction Detection) classification and regression trees (CART) was used to analyse spatial predictors, generate predicted percentage cover, and assess spatial patterns through mapping and clustering.

3.2 RPA data acquisition

RPA surveys were all conducted using a DJI Mavic drone, piloted by secondary supervisor Graham Hinchliffe. The RPA captured FMV at 2.7K resolution and 50 frames per second, improving temporal fidelity during frame-by-frame inspection. This improved the accuracy of frame extraction relative to the snorkeler's position within the RPA footage. In addition, the use of RPAs enabled extensive coverage of the fringing reef and provided high-resolution imagery suitable for shallow reef environments. With a battery lasting 20-35 minutes, transects could be carried out for extended periods, with surveys pausing to recharge the drone.

The flights were conducted at altitudes of 20 to 25 metres, as maintaining this height provided consistent visual overlap that captured the snorkeler as much as possible and enabled seamless integration with FMV processing. Multiple RPA flights were conducted each day to continuously capture the extent of the fringing reef and accommodate changes in environmental conditions. This RPA footage provided a general spatial overview of the

entire reef structure and served as a primary reference for spatially locating underwater transects across the reef (Figure 6).

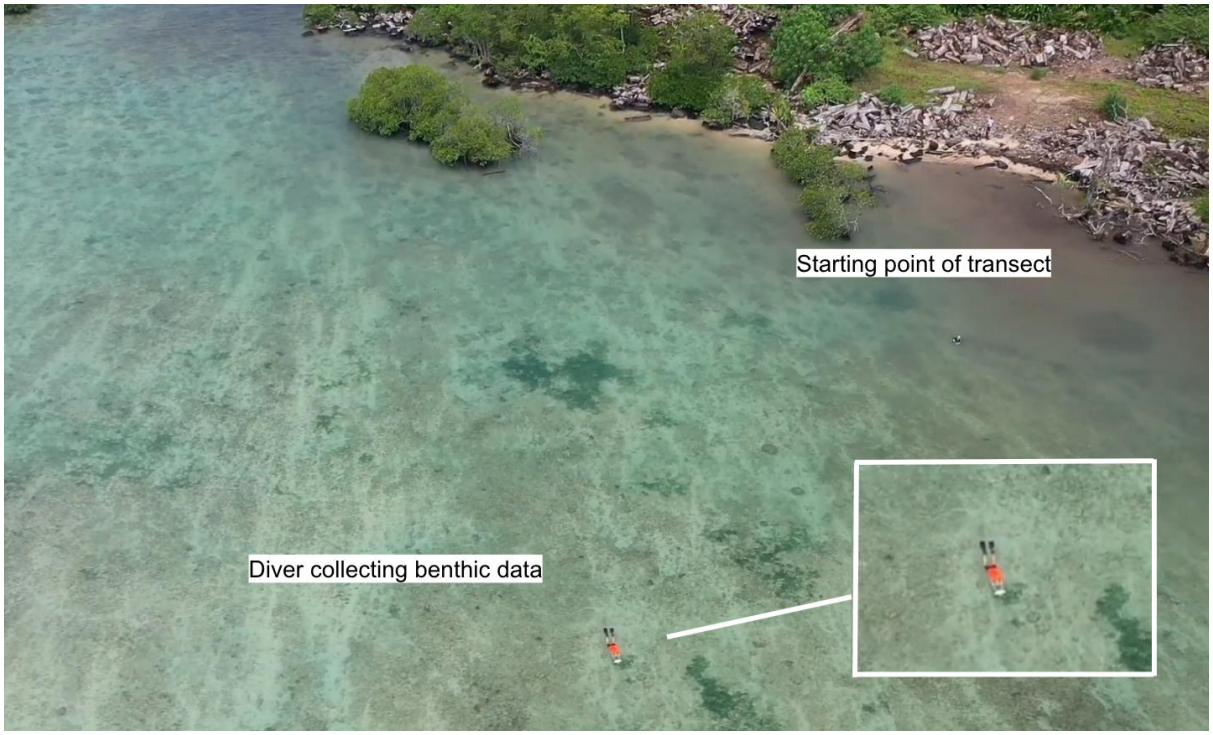

Figure 6. RPA aerial image of the northern fringing reef at Vavanga Village showing the start of the benthic survey transect. The diver collecting benthic data is visible within the frame, with the inset highlighting the diver at a closer scale.

All RPA flights were conducted by a licensed operator (Graham Hinchliffe), and all local aviation guidelines were followed safely. To maximise safety, all flights were recorded in favourable conditions, and flights were aborted in the event of unfavourable weather or strong winds. In addition, to ensure added security, all RPA footage recorded during the study period was downloaded to external storage and backed up at the end of each survey day. This safety check is essential to minimise potential data loss in the scenario of possible corruption.

3.3 Underwater video transects

Underwater video data were recorded by Grace Martin, Daniel Breen and Armagan Sabetian on a snorkel, using up to four GoPro cameras (Hero 8 and Hero 9) mounted on a battery-powered Sublue WhiteShark underwater scooter, configured to capture both the forward, downward and side-facing perspectives simultaneously (Figure 7) while the drone filmed from overhead.

Figure 7. Data collection team and equipment. Pictured from left to right is Daniel Breen (safety team), Grace Martin (snorkeler), holding the Sublue Whiteshark MixPro Underwater Scooter with a GoPro attached, and Graham Hinchliffe (drone pilot)

The dual camera system was carefully configured, with cameras oriented at approximately 90° to one another. This configuration allowed for additional angles to capture reef structure, both ahead of the snorkeler and directly beneath. This combination improves the accuracy of benthic classification, as classifying life forms from a single angle can be challenging.
This setup enabled continuous recording of reef structures and benthic composition while consistently maintaining a steady path along each transect. To aid this process, a handheld GPS unit and an underwater wristwatch were used to synchronise the temporal alignment between the underwater footage and the RPAs. This pairing ensured accurate synchronisation across datasets.
To match the RPA, each GoPro camera recorded underwater footage at 2.7K resolution and 50 frames per second, with stabilisation set to the lowest setting to minimise motion blur and object interference while maintaining the spatial detail necessary for benthic classification.
Similar to the RPA, the battery life of the underwater scooter and cameras was approximately 18-25 minutes before a battery exchange was necessary, providing ample continuous survey time to capture transects.

Over the eleven-day period in which data were recorded, 6 days of footage were dedicated to the northern fringing reef and selected for analysis. Each day, one or more transects were surveyed, haphazardly chosen to cover as much of the customary area as possible, working outwards from the Vavanga river mouth while safely traversing shallow reef and small waves. Sampling was not random, but rather opportunistic and still video frames collected at approximately 2 m intervals are not spatially independent (Figure 8).

Figure 8. Survey transect paths across the north- and south-fringing reefs at Vavanga Village, Solomon Islands.

Nevertheless, collecting georeferenced data at these spatial scales has advantages for mapping species and habitat distributions, but statistical sampling variances around the mean will be overly conservative. A workaround to address this issue, if required, might be to randomly subsample from the 4000 data points collected. RPA footage and the corresponding underwater video were reviewed, and the exact start and end times were identified to ensure a consistent timeframe across datasets for synchronisation (Appendix 1).

3.4 Synchronised aerial drone and underwater video recording

To synchronise RPA and underwater video recordings, the snorkelers signalled the start of their descent with a noticeable hand gesture or wave to both the GoPro lens and the drone, then immediately submerged. For this study, identifying the exact moment of submergence in each video served as the standardised starting point for each transect, providing a distinct, easily repeatable reference point across all videos (Figure *9*). Using VLC media player, timestamps at the time of submersion were logged in a Microsoft Excel spreadsheet.

Figure 9. Standardised hand gesture performed by the diver immediately prior to transect commencement, used as a visual synchronisation cue identifiable in both RPA and GoPro video footage.

The FMV extension in ArcGIS Pro was used to assign spatial coordinates to underwater camera locations from drone flight log data embedded in the aerial video (Figure 10) as described in Martin (2024). These include real-time kinematic (RTK) differential global positioning system (DGPS) coordinates, altitude, and camera orientation. To extract still images, an FFmpeg-based workflow was used, with intervals in the RPA video corresponding to the length of one snorkeler's body (Figure 11 and Figure *12*). Frame extraction was based on distance rather than time to ensure consistent spatial resolution between frames, all while maintaining adequate coverage of each transect when snorkeler speed varied. In rare situations where the drone adjusts, and the diver is no longer visible, no point was placed on the FMV, leaving small gaps with no frames for brief periods. In addition, outlier points deemed too far from the transect path were removed, as they would be inaccurate with respect to the diver's true position.

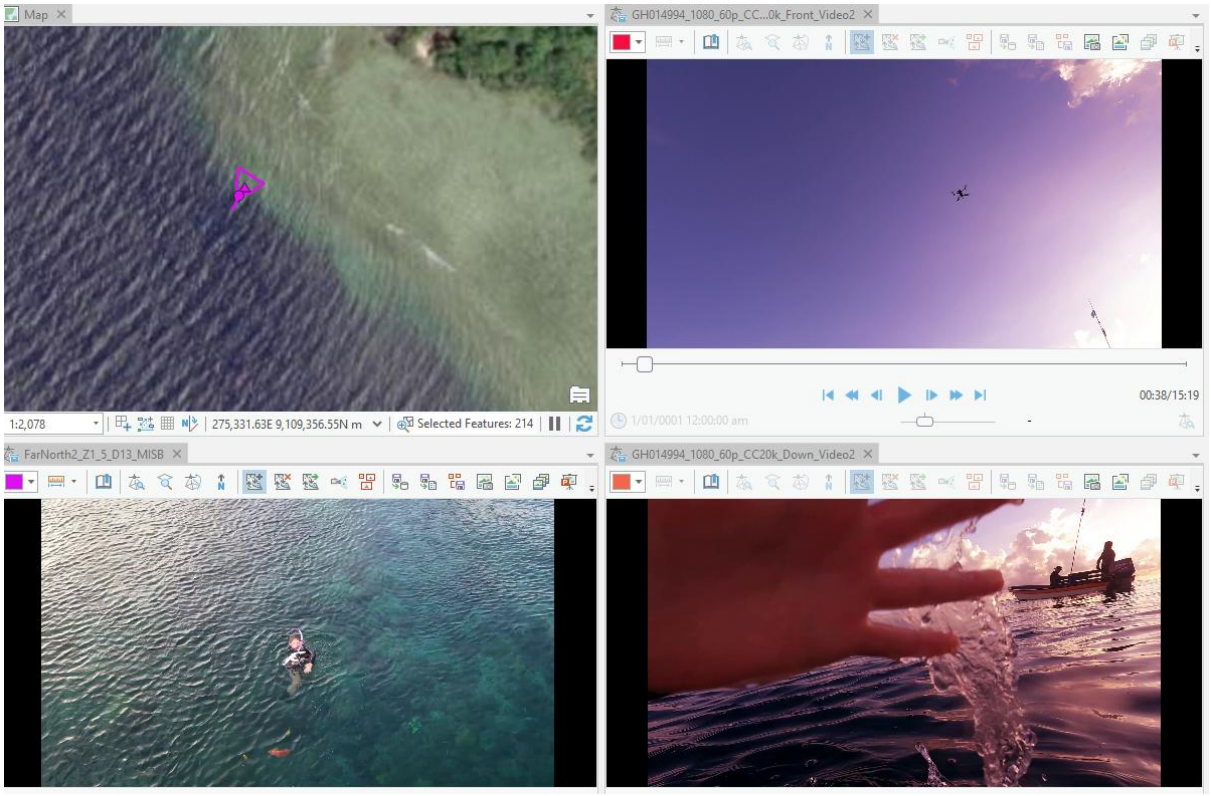

Figure 10. ArcGIS Pro display showing synchronised full-motion video (FMV) from RPA surveys and spatially referenced GoPro underwater footage, enabling cross-referencing between aerial and underwater perspectives. **Top left**: RPA flight and diver path overlaid on the ArcGIS Pro map, with the pink marker indicating the active spatial frame. **Top right:** synchronised georeferenced frame from the GoPro Front camera. **Bottom left:** RPA video frame capturing the diver along the reef transect. **Bottom right:** synchronised georeferenced frame from the GoPro down camera.

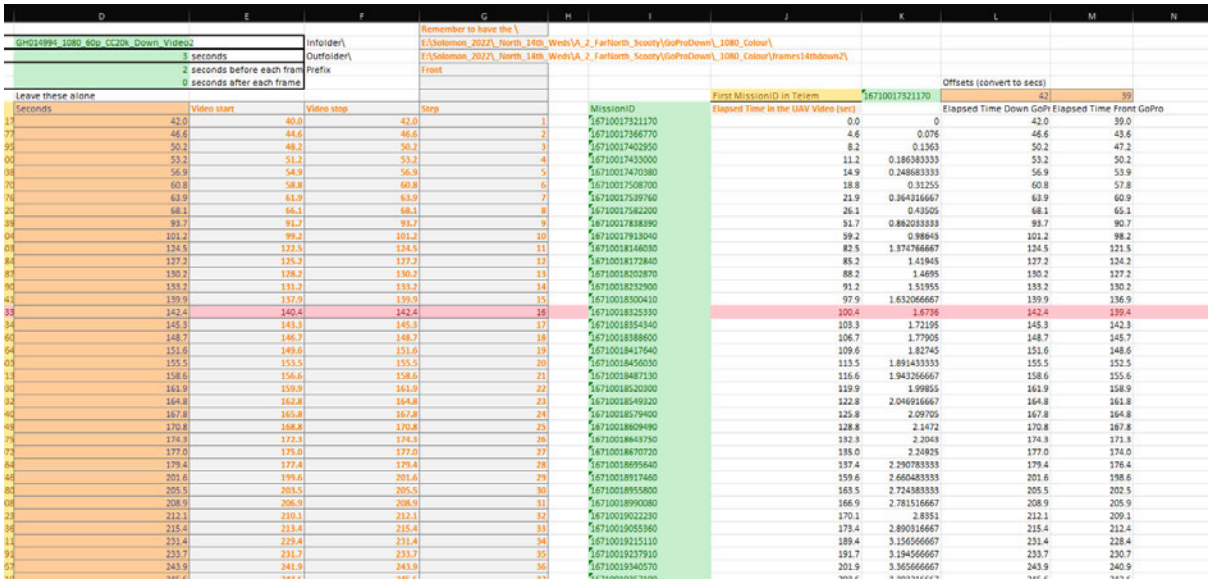

Figure 11. Spreadsheet-based FFmpeg workflow used to extract temporally synchronised still images from GoPro video footage. Video start and stop times were adjusted to account for the time offsets between the aerial and underwater videos.

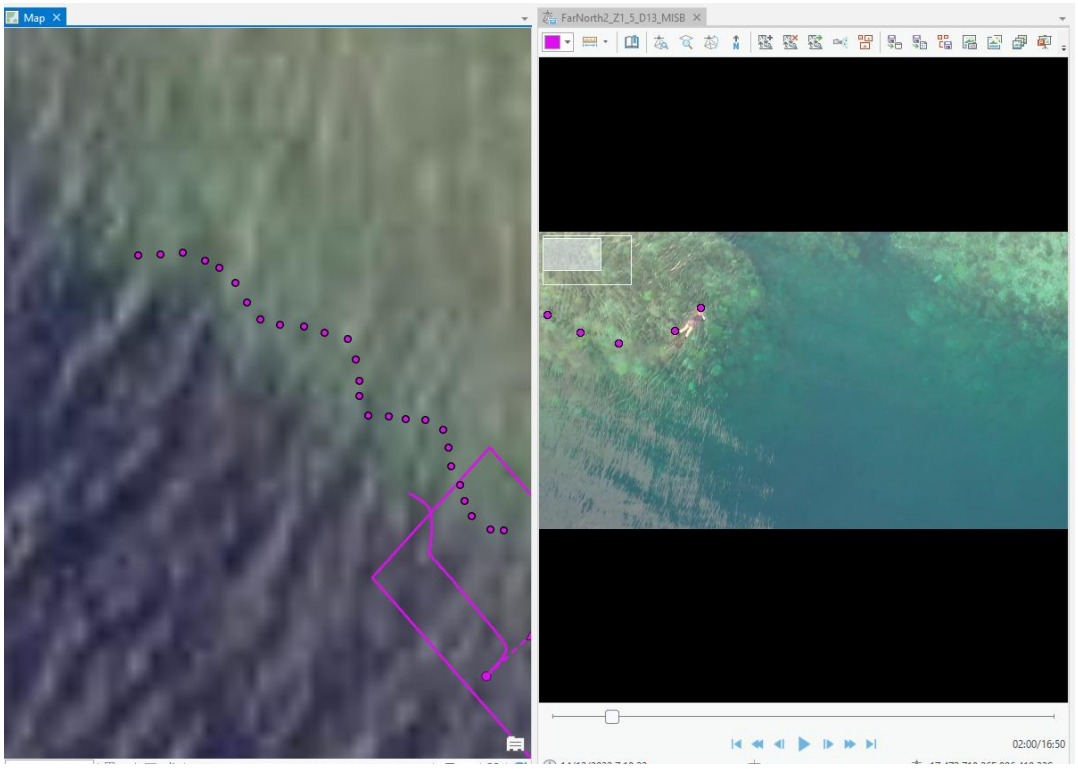

Figure 12. Example of point placement along a diver transect within ArcGIS Pro FMV, showing body-length–spaced sampling points traced along the diver's path based on synchronised RPA footage

Synchronised time stamps between aerial and underwater video, were used to transfer calculated spatial coordinates for the cameras to a Microsoft Excel database of unique codes for the still video images captured together with subsequent counts of identified lifeforms and substrata observed under points superimposed on each image.

Following synchronisation, 2,547 frames were successfully extracted after undergoing an additional quality control check prior to classification. All frames that exhibited excessive motion blur, reduced visibility or duplication were removed prior to benthic mapping. This quality control step ensured that only clear and representative frames were retained, thereby reducing the risk of misclassification and improving consistency across each transect. To improve the identification of biota, underwater video was corrected for colour to compensate for the absorption of red wavelengths with depth. Frames where one or more grid points were missing due to poor visibility from turbidity or lighting were retained throughout the extraction; each point non-visible was recorded as “Can’t tell” during the classification stage.

3.5 Manual benthic classification

Nine evenly spaced squares were digitally superimposed over each underwater image by Graham Hinchliffe. (Figure 13*).* Benthic organisms and substrata visible directly under the lower bottom corner of each square were classified visually from the video images (by A. Stockley, with assistance from D. Breen) and recorded as standard codes in the Excel database for that point and georeferenced image, along with spatial coordinates and other data.

Sessile benthic macro-organisms were identified to species where possible, or higher taxonomic levels or morphologies (e.g. massive *Porites*) where images did not provide enough clarity or detail. Abiotic categories included coral rubble, consolidated coral rock, sand and recently dead coral. Although these categories are not bereft of life, specific organisms were not readily visible in the underwater video at finer scales (Appendix 2). The classification followed the same process used in Grace Martin’s MSc thesis, ensuring methodological consistency between the two sites and studies.

With 9 classification points per frame, the dataset yielded 22,923 individual benthic point observations for analysis (Figure 14). For subsequent analyses, point counts for each benthic category were converted to percentage cover by dividing the number of points assigned to each category by the total number of visible points in each frame, then multiplying by 100.

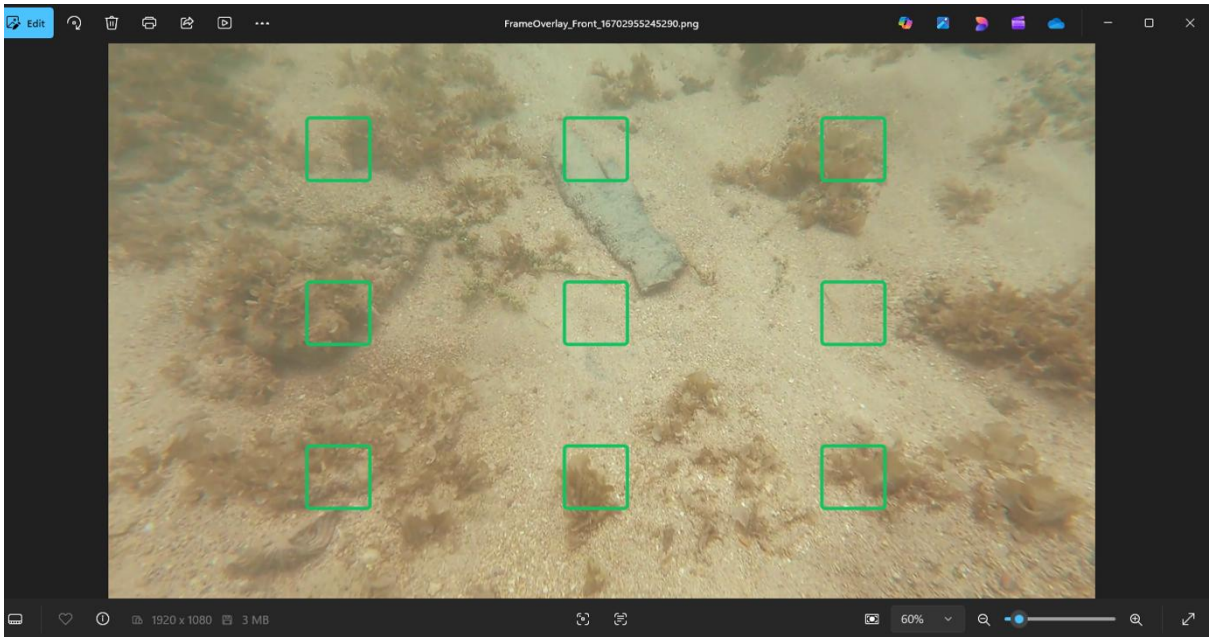

Figure 13. Extracted still image from GoPro Front video overlaid with a 3 × 3 point-sampling grid used for benthic classification. Each square represents a fixed sampling point used to assign benthic cover categories for subsequent percentage cover calculations.

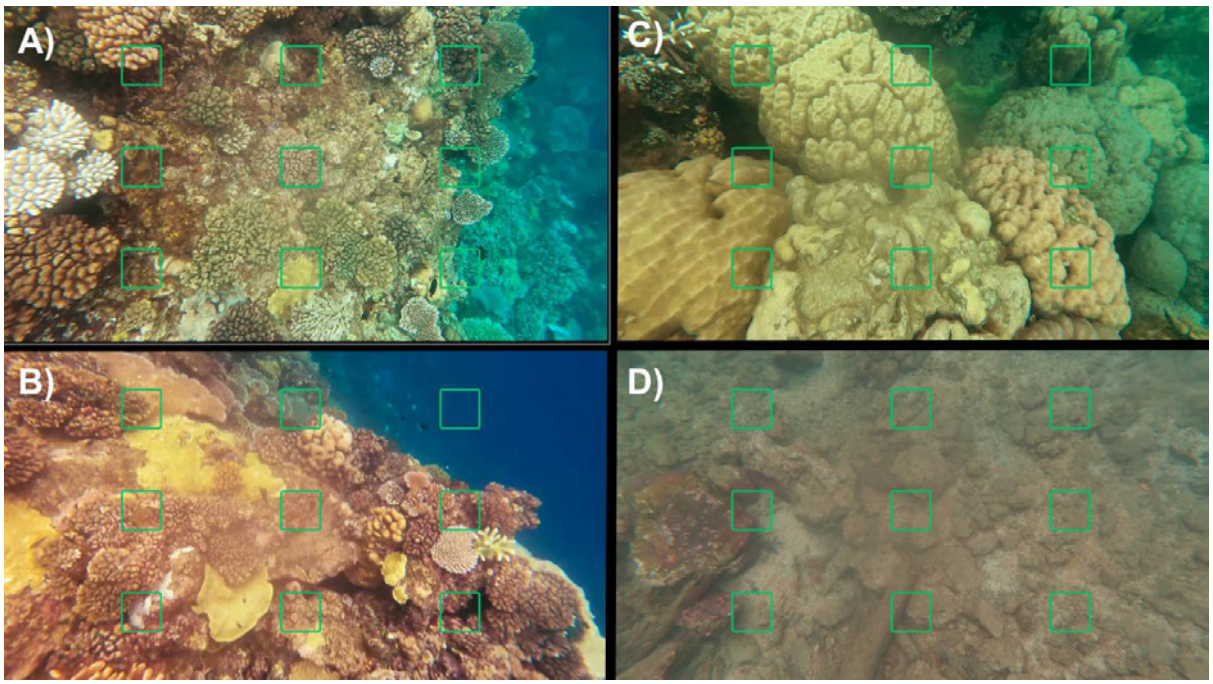

Figure 14. Underwater video frames (12 December) illustrating benthic composition and application of the point-based classification grid. Panels show contrasting benthic assemblages: (A) coral rubble and mixed coral communities; (B) coral assemblages dominated by *Porites* (massive), *Pocillopora* and *Acropora*; (C) *Porites*-dominated reef; and (D) coral rubble-dominated substrate. Green squares indicate classification points used for benthic analysis.

3.6 Classification and regression tree (CART) analysis

For each georeferenced underwater video image, the proportion of manually classified benthic taxa and substrata under nine systematic points was used to calculate percentage cover for, where possible, different species, genera, families and substrata. Results for the northern reef flat were combined with similar data from Martin (2024) for the reef flat south-east of the Vavanga River, yielding a total of 4,011-point locations. Percentage cover for different taxa and substrata at all points was overlaid on high-resolution drone photomosaics, satellite imagery (ESRI basemap), and predicted means from spatial classification and regression trees, as described below.

A line feature was drawn approximately parallel to the seaward extent of the reef crest and upper reef slope in ArcGIS Pro. The 'Near' function in ArcGIS Pro was then used to estimate the closest distance in metres of each point and associated percentage cover from the line along the reef crest.

A second line was drawn perpendicular to the coast at the northern bank of the river at Ghatere, the neighbouring village 2.5 km south of Vavanga, as a second spatial axis. The distance to this line, in metres, was assigned as a second spatial predictor variable to every point in ArcGIS Pro. A similar approach was used to model 70 marine bioregions of the Great Barrier Reef World Heritage Area, based on coral, fish, algae, seagrass, and other taxa, in response to proportional distance offshore and along the south-east axis of the reef (Kerrigan et al., 2010).

Distances across and along the reef and the response variables (percentage cover of taxa and substrata for each point) were analysed in IBM SPSS Statistics v 31.02 using Chi-square Automatic Interaction Detection (CHAID). This recursively partitions points into statistically distinct groups based on associations between the predictor variable (spatial location) and the response variable (percentage cover).

The minimum parent node size was set at 300 observations, and the child node size was set at 200 observations, and the depth of trees was limited to 2 or 3 splits. This conservative approach was done to identify dominant spatial patterns in benthic distributions and to reduce overfitting, given the high number of observations and spatial dependencies among points. A ten-fold validation was used to estimate how well decision tree predictions performed using subsets of the data.

A 2 m^2 tessellation grid of square polygons was created to include all data points within its extent, and the Near command in ArcGIS Pro used to assign distances in metres from the reef crest and the Ghatere River to each square polygon. For each benthic category, the mean percentage cover within each distance category from each split in the classification

and regression trees was assigned to the corresponding square polygons in the tessellation according to their distance to the reef crest and Ghatere.

The mean values of percentage cover for different partitions in the CHAID trees were then mapped in the tessellation, and means were coloured according to increasing mean cover. The original data points for video frames were overlaid on the populated tessellation, which was, in turn, overlaid on photo mosaics and satellite imagery to visually assess the success of the classifications.

3.7 ReefCloud classification of benthic biota and substrata

ReefCloud, an AI-based machine-learning benthic image classification platform developed by the Australian Institute of Marine Science (2025), was used to train an AI model on a subset of 195 manually classified images. Each image was first manually annotated using ReefCloud's benthic class definitions, which align with the manual classification, allowing for a direct, consistent comparison between manual and machine-assisted classification outputs. After training, the model was provided with 2,404 images from all 14 video transects on the fringing reef north of the river at Vavanga. ReefCloud's learning framework then independently improved model recognition of benthic categories, differentiating live coral morphologies and non-coral substrata.

Due to the time-intensive calibration and training process, ReefCloud was used as a complementary tool rather than as a replacement for manual classification. It was used to assess the feasibility of human-AI hybrid monitoring workflows while retaining human oversight in data-limited reef environments. The model's performance was evaluated by comparing automated classification with manual annotations using F1 scores, percentage cover, and a confusion matrix that directly measures the presence and absence of coral at the image frame level. These outputs were interpreted as complementary rather than definitive, with manual classification remaining the primary dataset upon which both spatial modelling and statistical analysis are based.

4 Results

4.1 Study area

Datasets were collected across the north and south fringing reefs adjacent to the Vavanga Village, Kolombangara Island, in the Solomon Islands' Western Province. The fringing reef forms part of a broader fringing reef system surrounding the small river mouth on both sides. Previous research conducted by Martin (2024) focused on estimating the percentage cover of biota and substrata on the fringing reef south of the river at Vavanga. For this study, drone and underwater video were used to estimate percentage cover on the northern side of the Vavanga River.

4.2 Classification and regression trees

CHAID Classification and regression tree (CART) models (Figure 15-Figure 18) for data from this study and Martin (2024) were combined to map broad spatial patterns in benthic cover on the north- and south-fringing reefs on either side of the river at Vavanga. The trees divide and subdivide points for all video frames in the total area surveyed into areas of similar mean percentage cover, according to distance from the reef crest and from Ghatere, 2.5 km south of Vavanga.

For reasons of space, we present here only trees for the percentage cover of hard coral *(Porites* spp.), seagrass, and macroalgae; trees for additional benthic categories are attached in the Appendices. All tree partitions had Bonferroni-adjusted P values <0.01, and most values were much smaller, partly due to the very high number of observations (n=4011). The spatial co-dependence of neighbouring points is also likely to make these tests more liberal than they would be under random sampling. For these reasons, we do not discuss significance values as an inferential tool and use the trees in an exploratory approach to mapping and data visualisation.

The CART model for percentage cover of hard coral (Figure 15) identified distance from the reef crest (Dis_Crest) as the primary predictor of coral distribution across the fringing reef (Adj. $p < 0.001$, $F = 483$). The highest predicted hard coral cover (35.9%) occurred within 17 m of the reef crest. Within this zone, a secondary split based on distance from the southern baseline at Ghatere separated southern areas from the far northern section of the study area, where predicted hard coral cover decreased to 21.7%.

As the distance from the reef crest increased beyond 17 m, mean hard coral cover declined considerably. Intermediate zones between 17 to 55 m had predicted hard coral cover

ranging from 19% and 29% cover. Sites situated more than 55 m from the crest displayed substantially lower values, decreasing to below 4%, and as low as 0.2% across increasing distance classes. Overall, mean hard coral decreased with increasing distance from the reef crest.

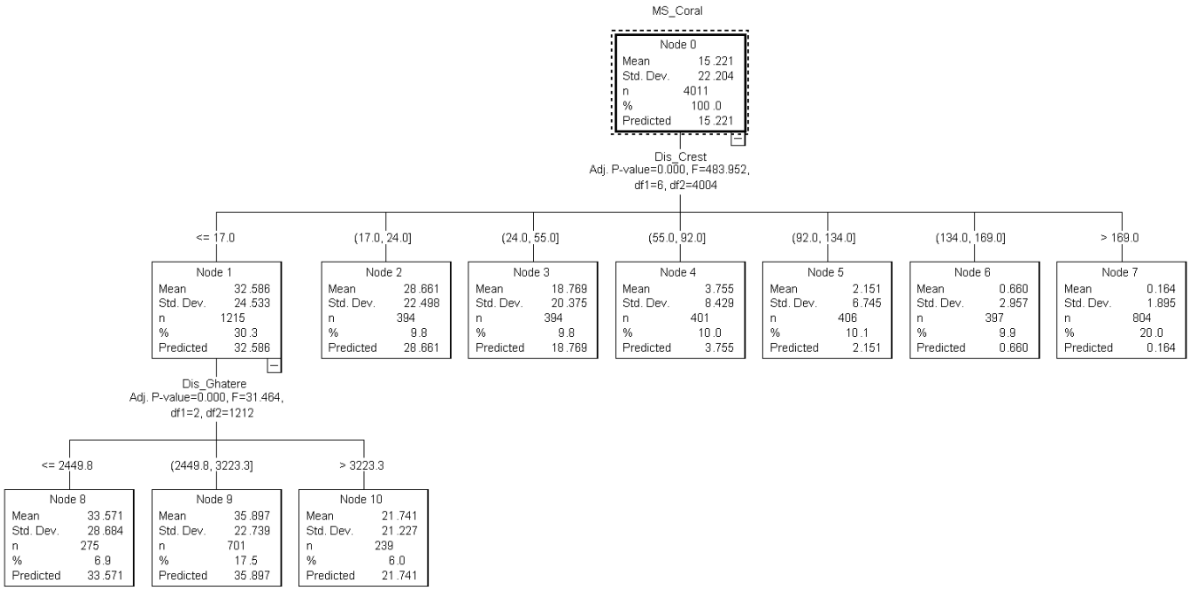

Figure 15**.** Classification and regression tree (CART) model predicting the percentage cover of total hard coral across the north reef flat. The primary split occurred along distance from the reef crest (Dis_Crest), with a secondary subdivision by distance from the Ghatere river outlet (Dis_Ghatere). Node values display the mean predicted percentage cover, the standard deviation, and the sample size (n).

The CART model for *Porites* spp. (Figure 16) identified Dis_Crest as the primary predictor of percentage cover (Adj. $p < 0.001$). The highest predicted *Porites* cover (12.3%) occurred within 17 m of the reef crest. Within this area, a secondary split based on distance from Ghatere separated areas with predicted *Porites* cover between 4.5% and 12.3%. Beyond 17 m from the crest, *Porites* cover in intermediate zones (17–134 m from the reef crest) ranged between 2% and 4.9%, while sites located more than 134 m from the reef crest showed much lower values, decreasing below 1%. Overall, *Porites* cover decreased with increasing distance from the reef crest.

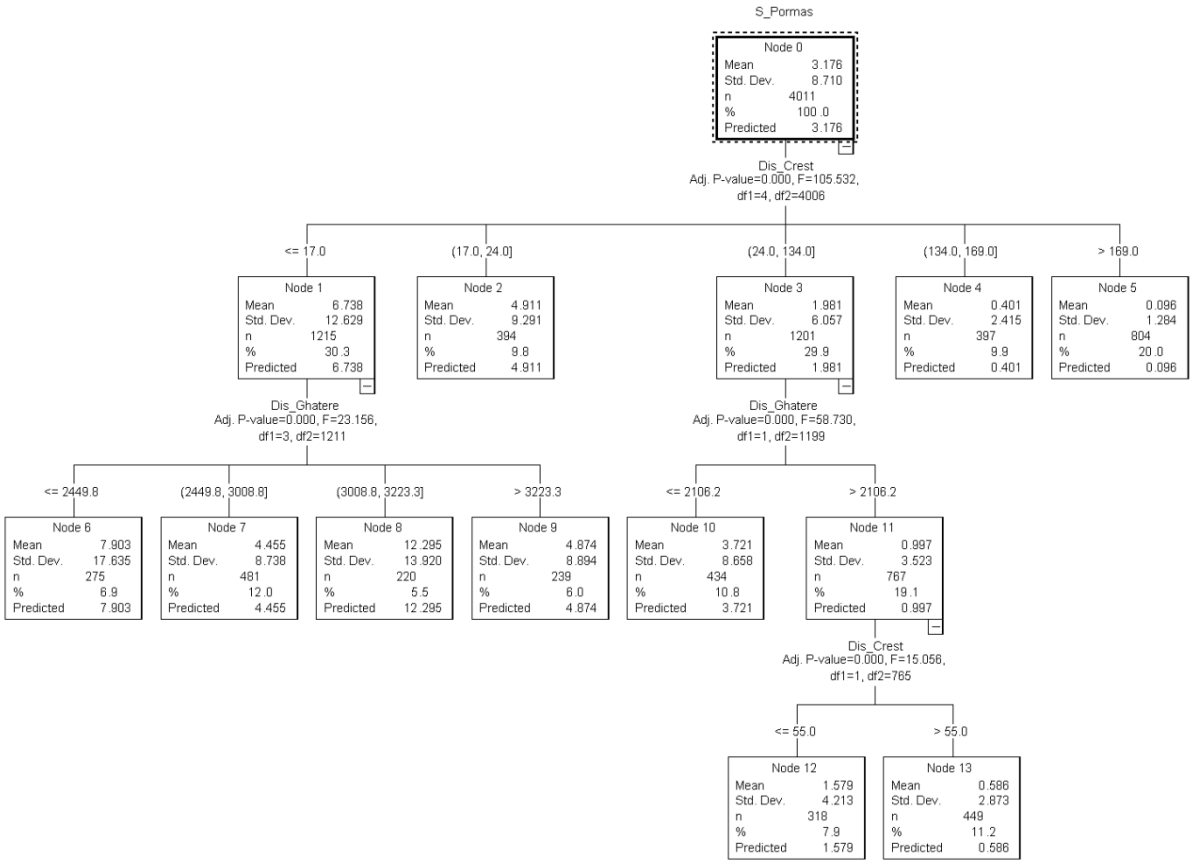

Figure 16. Classification and regression tree (CART) model predicting the percentage cover of *Porites* spp. across the north reef flat. The primary split occurred along distance from the reef crest (Dis_Crest), with secondary subdivision by distance from the Ghatere river outlet (Dis_Ghatere). Node values display the mean predicted percentage cover, standard deviation, and sample size (n).

The tree for percentage cover of seagrass (Figure 17) identified distance to the reef crest as the primary predictor (Adj. $p < 0.001$). Seagrass was largely absent in zones near the reef crest (≤55 m). Beyond 55 m from the reef crest, predicted seagrass cover increased progressively, from 1.9% at 55-92 m to 12.9% at 134–169 m, 38.4% at 169–212 m, and a maximum of 95.4% at the greatest inshore distances (>212 m). Overall, predicted seagrass cover increased with increasing distance from the reef crest.

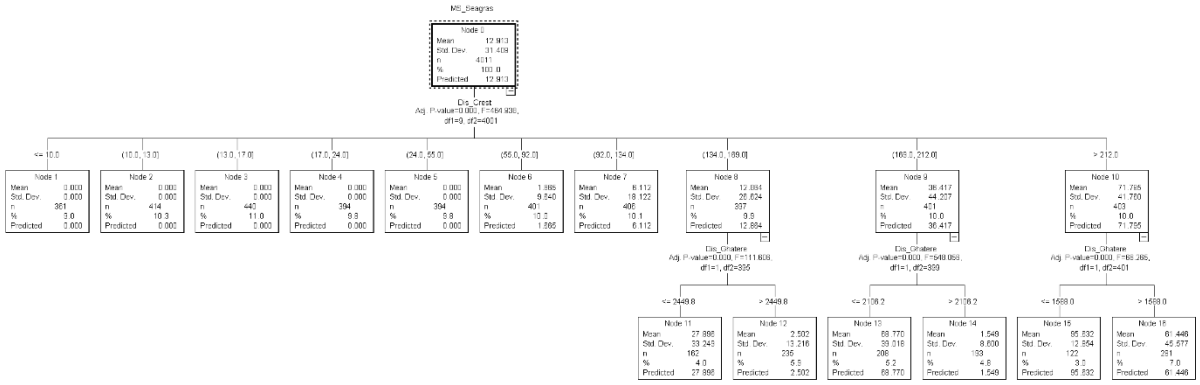

Figure 17**.** Classification and regression tree (CART) model predicting percentage cover of seagrass across the north reef flat. The model identified distance from the reef crest (Dis_Crest) as the primary predictor. Node values display the mean predicted percentage cover, standard deviation, and sample size (n).

The CART model for percentage cover of macroalgae (Figure 18) identified distance from Ghatere (Dis_Ghatere) as the primary predictor (Adj. $p < 0.001$, $F = 232.086$). Mean macroalgae cover was lowest at sites ≤2449.8 m from Ghatere (0.7%) and at the greatest distance (>3223.3 m; 0.3%). The highest predicted macroalgae cover (30.1%) occurred between 2449.8 and 2829.0 m from Ghatere.

Within this zone, a secondary split based on distance from the reef crest identified areas with predicted macroalgae cover ranging from 0.9% within 24 m of the reef crest to 30.1% between 24 and 134 m, before decreasing to 20.0% between 134 and 169 m. Overall, macroalgae cover varied across both distance from Ghatere and from the reef crest but was most abundant at intermediate distances between the reef crest and shore.

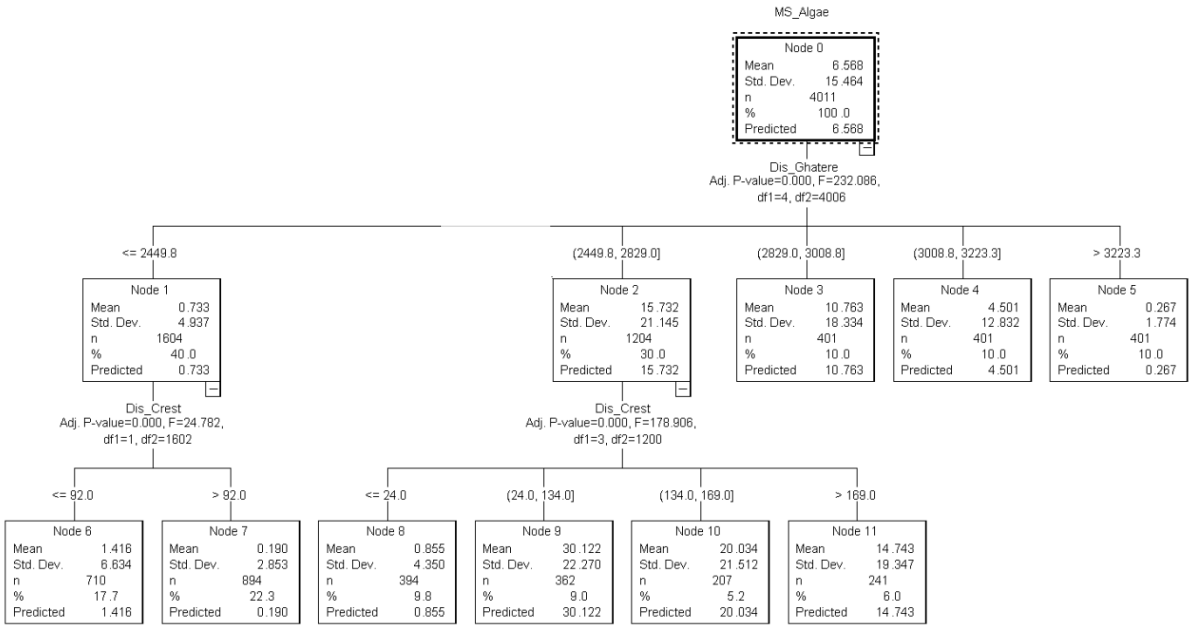

Figure 18. Classification and regression tree (CART) model predicting percentage cover of macroalgae across the north reef flat. The primary split occurred along distance from the Ghatere river outlet (Dis_Ghatere), with secondary subdivision by distance from the reef crest (Dis_Crest). Node values display the mean predicted percentage cover, standard deviation, and sample size (n).

4.3 Spatial distribution of corals, seagrass and macroalgae.

Maps of broad, contiguous areas of fringing reef with similar mean percentage cover of different corals, seagrass, macroalgae and substrata were categorised by the CHAID splits in the across and along reef predictor variables, i.e. distance to Vavanga and distance to the northern side of the river at Ghatere, the village 2.5 km to the south. Values for mean percentage cover from each CHAID tree partition (branch) are assigned to 2 km^2 squares tessellated for the study, according to the boundaries of each CHAID group defined by distance to the reef crest and from Ghatere (Figure *19-Figure 29*). For sufficiently abundant taxonomic groups, categories for different means are coloured (with 50% transparency) on the maps, with colour intensity increasing with increasing mean cover.

Mean percentage cover for the CHAID-classified areas was overlaid on a satellite image (ArcGIS Pro, ESRI) of the study area. Although higher resolution drone photomosaics were also available, their detail tended to obscure some of the underwater video data points and classifications. The percentage cover for each individually georeferenced video frame and benthic category is overlaid as point features, coloured from blue to red, with intensities ranging from 0 to 100% cover.

Total live coral

Although soft octocorals and hydrozoan corals were recorded in low densities (on fore reef mostly) most corals were scleractinian hard corals and we present data only for these. Mean percentage cover of hard corals is highest along the reef crest and upper fore reef slope for the northern and southern fringing reefs (~35%) but decreases on the most northern reefs of the study area (22%; Figure *19*). Hard coral cover declines rapidly inshore of the reef crest to 28% between 17 and 24m from the crest; 18.8% between 24 and 55m; 3.8% within 92m to less than 1% beyond 134m from the crest. There were also areas of relatively high coral cover along the entrance passage to the river at Vavanga, including a large (4m long) foliose *Montipora* colony; large *Porites* boulder coral and *Acropora* staghorn on the south side of the river, and large patches of smaller boulder corals and whorled *Montipora aequituberculata.*

Overall, though, this pattern demonstrates a strong cross-reef zonation of decreasing mean hard coral cover with distance from the reef crest, with some variation in cover along the reef crest as well. The individual point cover estimates align well with the generalised classification and regression tree-coloured zones. There is, as expected, considerable variation among video frames, but also clusters of similar percentage cover at medium spatial scales.

***Acropora* spp.**

The percentage cover of *Acropora spp.* was highest within 24m of the reef crest but varied from 12% at the southern end of the reef, peaking at 17% around the river at Vavanga and gradually decreasing to 12% at the far northern end of the study area (Figure *20*). This included a range of species and life forms, including branching (e.g. *A. florida*), plate (*A. hyacynthus*), and corymbose (*A. aculeus*) colonies of a range of sizes at and below the reef crest. *Acropora spp.* also occurred up to 55m inshore of the reef crest (8%) but dropped to less than 1% between there and the shore. Colonies inshore of the reef crest were mostly small, low-lying colonies and either robust (e.g. *A. gemmifera, A. monticulosa*) or rapidly colonising, often by fragmentation (*A. verweyi*).

Due to low tides and swell, few video transects on the southern reef flat intersected the reef crest, and so estimates here are based on fewer data sampling a smaller area. In comparison, the north reef crest displayed a near-continuous band of *Acropora* points, with significant clusters of higher point densities aligning closely with areas of moderate to high predicted percentage cover. This pattern indicates a robust distribution of *Acropora* along the Vavanga reef crest, and to a lesser extent, on the outer reef flat, with few colonies inshore.

Pocillopora spp.

The cover of *Pocillopora spp*. (Figure *21*), was highest within 13m of the reef crest but slightly higher (12%) in the southern part than in the northern part (9%) of the study area. Cover was also high (8.5%) up to 24m inshore and within 55m of the reef crest (5%), but dropped to near zero across the remaining reef flat. These were robust corals known for their wide distribution, colonising abilities, and adaptation to high-energy wave environments, particularly in this case, *P. verrucosa, P. meandrina*, to a lesser extent, *P. damicornis* and on the reef crest occasionally, *P. eydouxi.* Again, as some transects on the southern reef flat did not extend to the reef crest, the region's representative coverage of this area is less.

Porites spp.

Percentage cover of *Porites* spp. was highest within 17m of the reef crest but varied along the reef between 5 and 12%. Cover remained at 5% within 24m of the crest, averaged 2% up to 134m away, but less than 1% further inshore. *Porites* exhibited a wider spatial distribution than *Acropora* and *Pocillopora*, with cover occurring along the reef crest and extending across the adjacent reef flat (Figure *22*). In comparison with both *Acropora* and *Pocillopora*, *Porites* occurrences on the reef flat were more frequent along the southern reef as opposed to the northern flat. The mapped point estimates align with the tree means and point clusters of high cover are evident north of the river and along the river pass, including a

large cluster of medium-sized *(2-3m) Porites* boulder corals at the northern entrance to the channel.

Montipora

Montipora spp. (Figure *23*) peaked at 4% around the river at Vavanga and further north on the reef crest, but cover was generally around 1% or less over much of the crest and northern reef flat. There is a very large 4m long flat foliose Montipora colony in a cove of the southern reef pass, and a large patch of whorled *M. aequituberculata* on the northern side of the pass, evident in the video point cover estimates that would contribute to these areas with higher cover. Branching *M. digitata* did occur on the mid to outer reef flat south of the river, but colonies were small and percentage cover low.

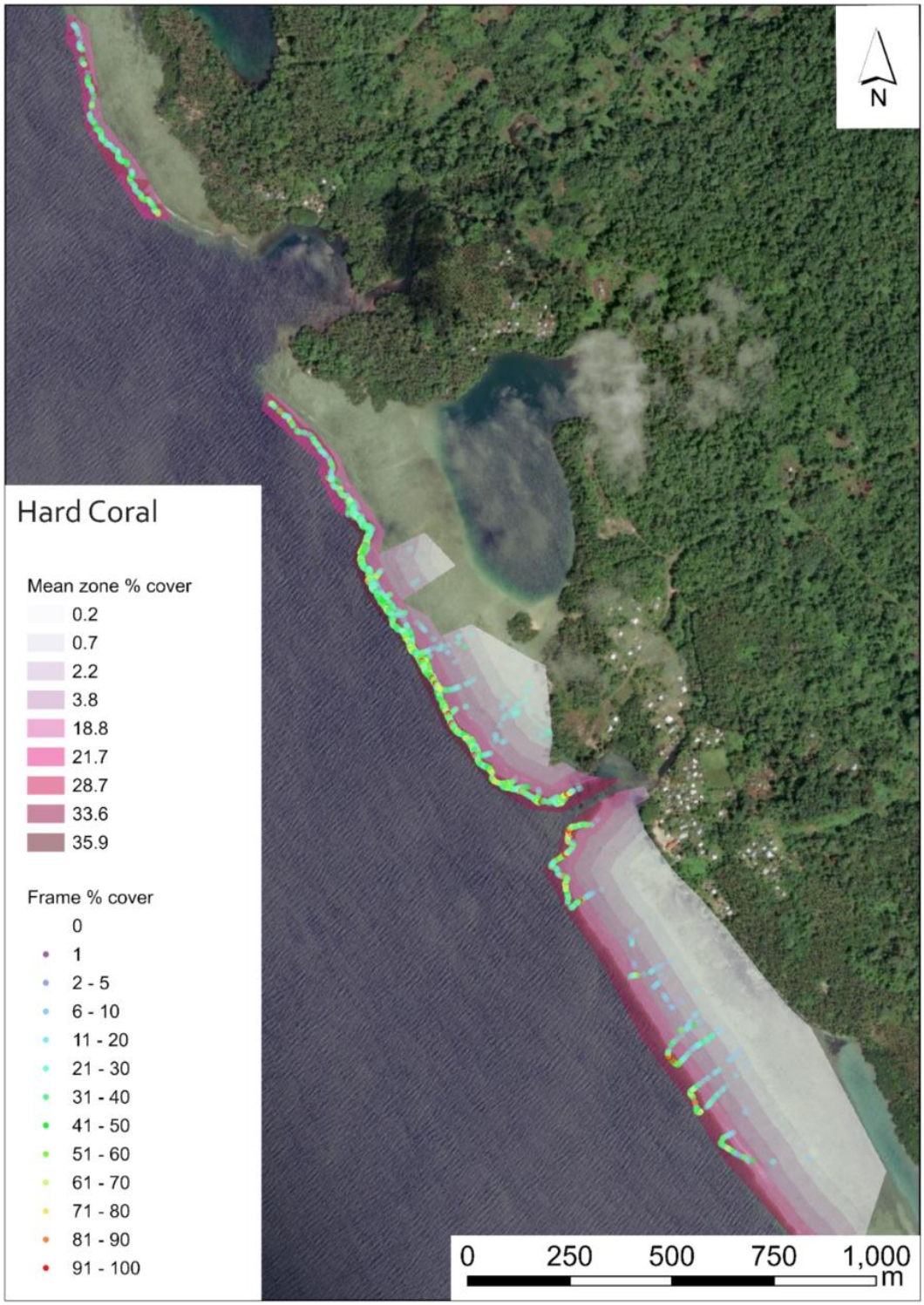

Figure 19. Spatial distribution of predicted hard coral percentage cover across and along the reef derived from classification and regression tree (CART) model outputs. Shaded polygons represent the mean predicted percentage cover within each CART-derived spatial zone, while point symbols indicate hard coral percentage cover calculated from individual underwater video frames extracted along survey transects.

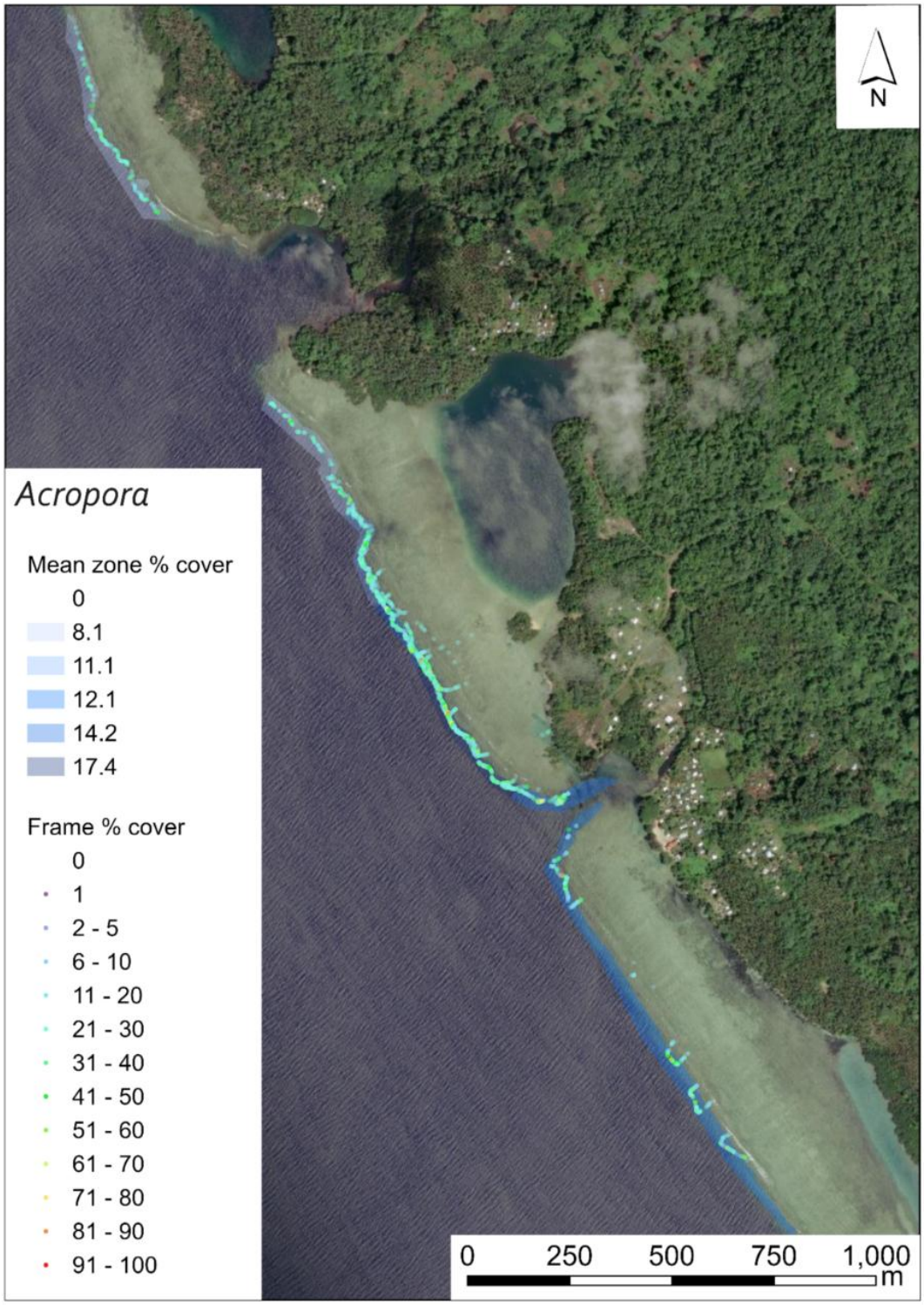

Figure 20**.** Percentage cover of *Acropora* spp. derived from individual underwater video frames overlaid on the mean percentage cover predicted from classification and regression tree model outputs.

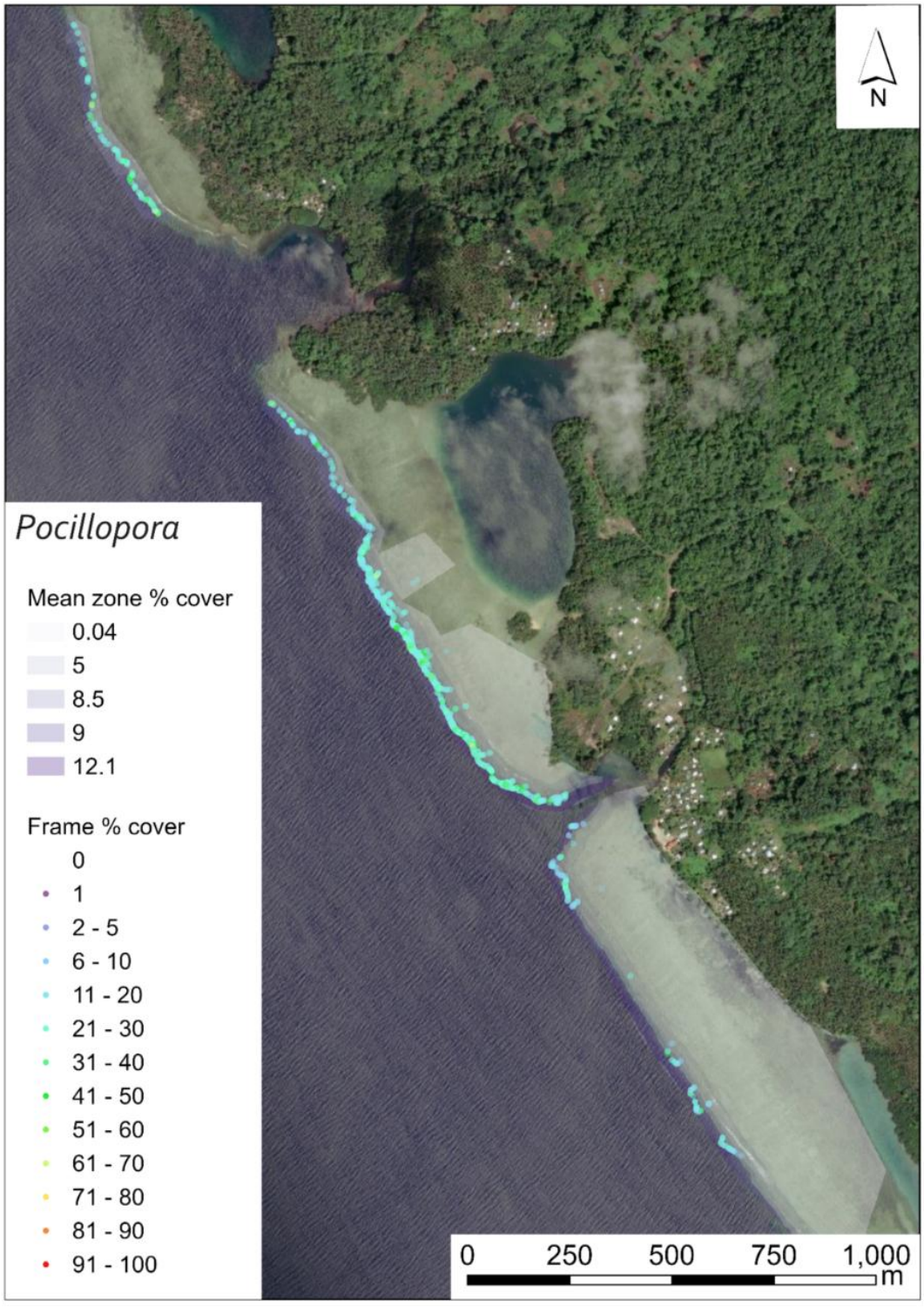

Figure 21. Percentage cover of *Pocillopora* spp. derived from individual underwater video frames overlaid on the mean predicted percentage cover generated from classification and regression tree (CART) models.

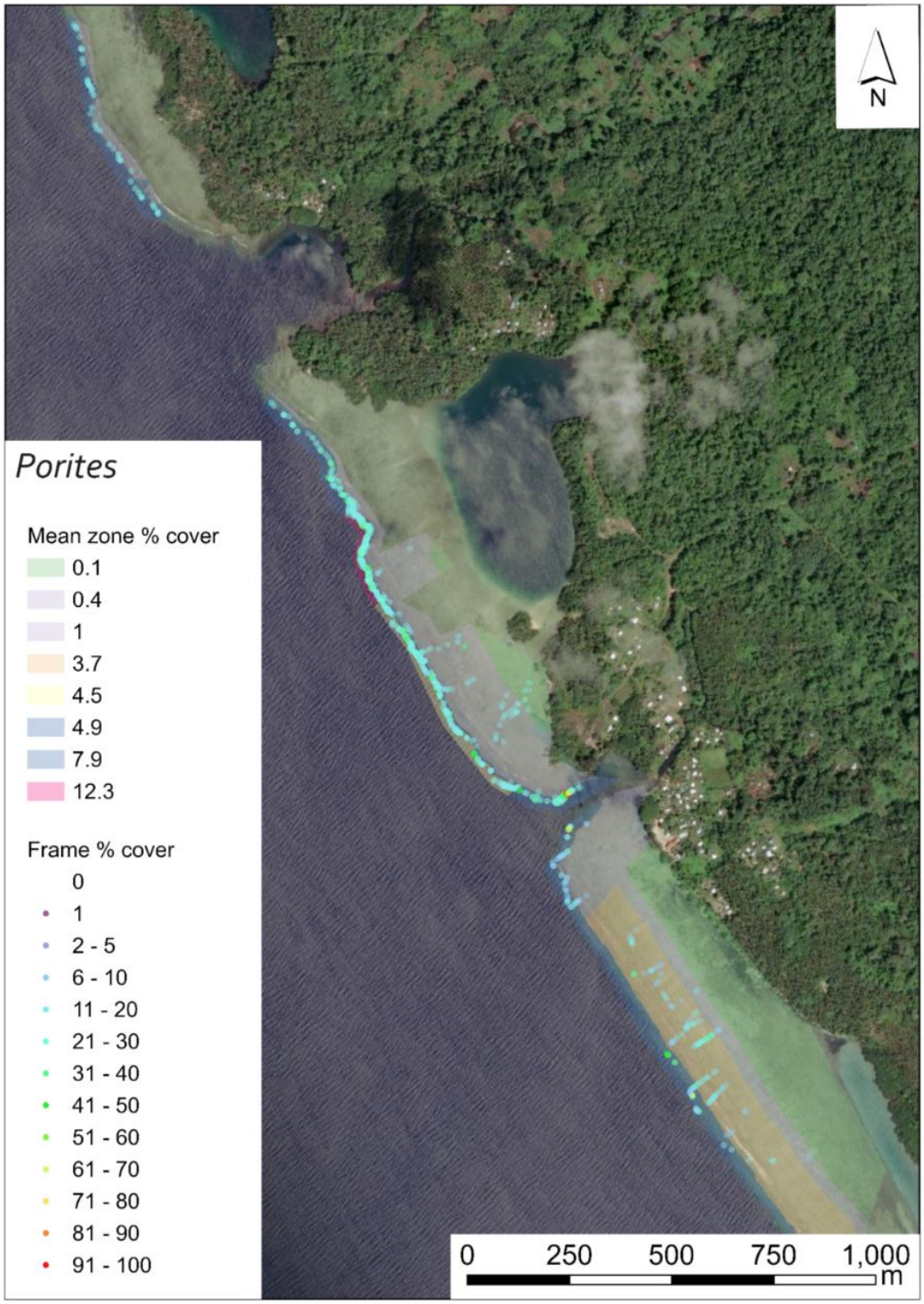

Figure 22. Percentage cover of *Porites* spp. derived from individual underwater video frames overlaid on the mean percentage cover predicted from classification and regression tree (CART) models.

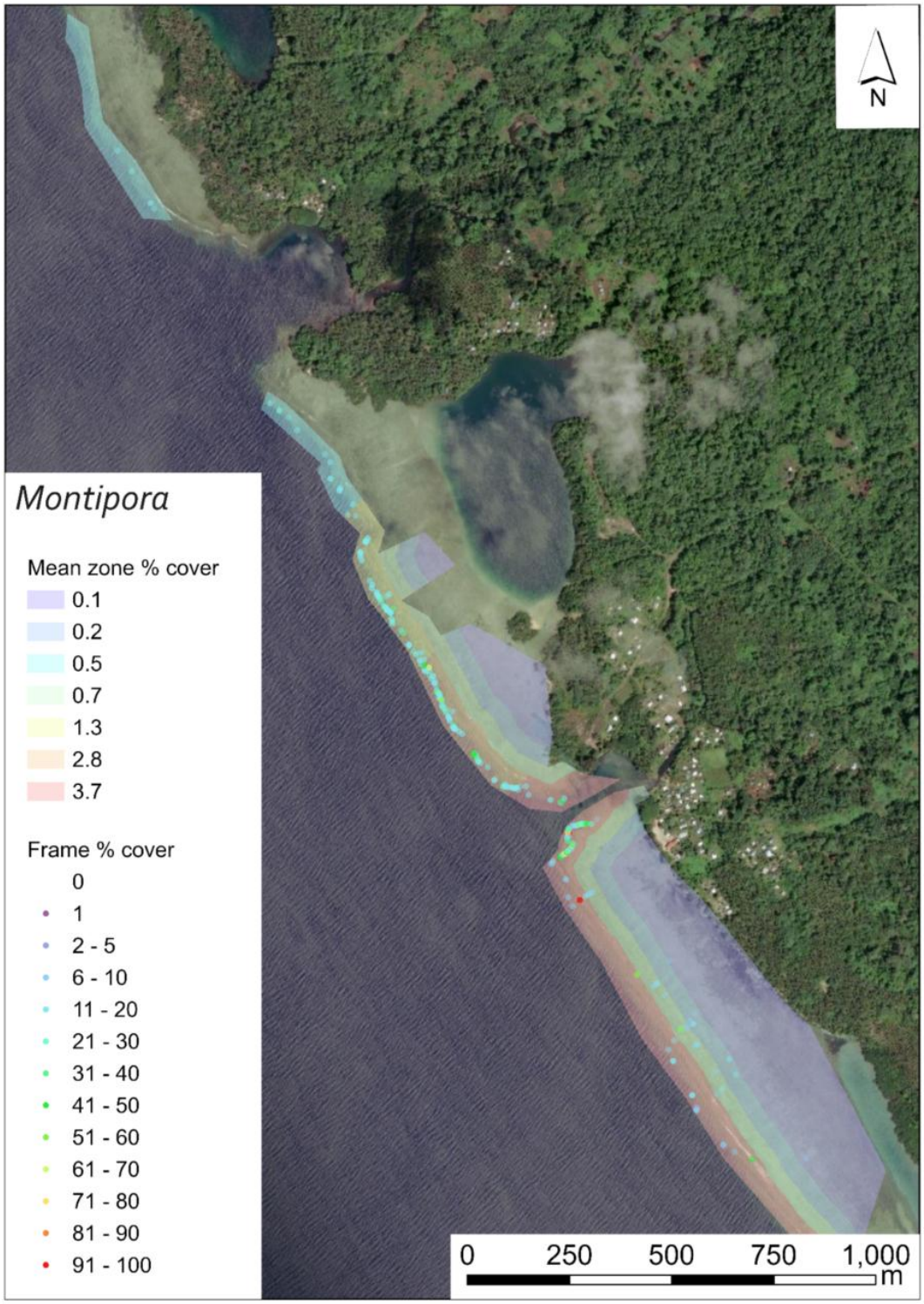

Figure 23. Percentage cover of *Montipora* spp. derived from individual underwater video frames overlaid on the mean percentage cover predicted from classification and regression tree (CART) models.

Seagrass

Seagrass was concentrated predominantly along the southern reef flat, where extensive patches were observed across the shallow inner reef flat. In comparison, the northern reef contained only isolated, sparse seagrass points (Figure *24*). South of the river, mean seagrass cover ranged from 0% at the reef crest to 0.6% between 55 and 92m from the crest to 6% cover between 92 and 134m; 27% cover up to 169m; 68% cover up to 212m from the crest to 95% cover between there and the shore. A high percentage cover of coarse sand was associated with the seagrass beds. Seagrass rarely occurred within 55m of the reef crest.

Macroalgae

Macroalgae cover was highest on the reef flat for both the northern and southern reefs, with very low macroalgal cover on the reef crest (Figure *25*). Observed macroalgal points closely aligned with predicted areas of mean cover. The highest point densities and mean cover occurred within the middle reef flat zones, either side of the river, between 24 and 134m of the reef crest (30% cover); decreasing to 20% up to 169m; and 15% macroalgal cover between there and the shore. While the southern reef flat featured extensive macroalgal zones, the northern reef flat was not surveyed as thoroughly, and interpolations do not cover much of it. The reef crest had consistently low macroalgal cover, although we did not record encrusting coralline algae and probably other, more cryptic species.

Halimeda spp.

Mean percentage cover of *Halimeda* spp. was generally less than 1% except on the mid to outer reef flat, 24 to 92 m from the reef crest, either side of the river at Vavanga (5%). Mean cover for the reef flat further north (2%) was lower but is probably an artefact of less sampling inshore (Figure *26*). Although there was less than 1% on most of the reef crest itself, there were large beds of Halimeda on the forereef slope below 3m that may not have been sampled.

Padina sp.

Padina sp. (Figure *27*) was most abundant on the reef flat with less than 1% cover within 24m of the reef crest and low cover (1.5%) within 55m of the crest. Cover increased inshore to 11% between 55 and 92m and peaked between 92 and 212m from the reef crest at 19% and 10% north and south of the river, respectively. Between 212m and the shore mean cover fell to 4%.

Sargassum sp.

Sargassum was largely restricted to the reef flat, with few occurrences on the reef crest (Figure *28*). Cover peaked at 14% on the mid reef flat 92 to 134m from the crest and on the outer reef flat 55 to 92m from the reef crest south (13%) and north (6%) of the river. Cover decreased inshore to 4 % from 134 to 169m and fell to less than 1% between there and the shore.

Turbinaria ornata

Mean cover of the spiny, tough macroalgae *Turbinaria ornata* (Figure *29*) was greatest between 24 and 92m from the reef crest at 2-3% but less than 1 % elsewhere. Occurrences were most apparent on the southern reef, probably as samples included more of the reef flat. Most occurrences were concentrated within the narrow region between the shallow reef flat and the reef crest, with few occurrences recorded on the reef crest itself, and entirely absent across the inner reef flat.

Predicted percentage cover remained consistently low across the study area, while localised peaks corresponded to observed point clusters, predominantly along the southern reef. This restricted distribution demonstrates that *Turbinaria ornata* was primarily associated with the transitional zone between the reef crest and reef flat.

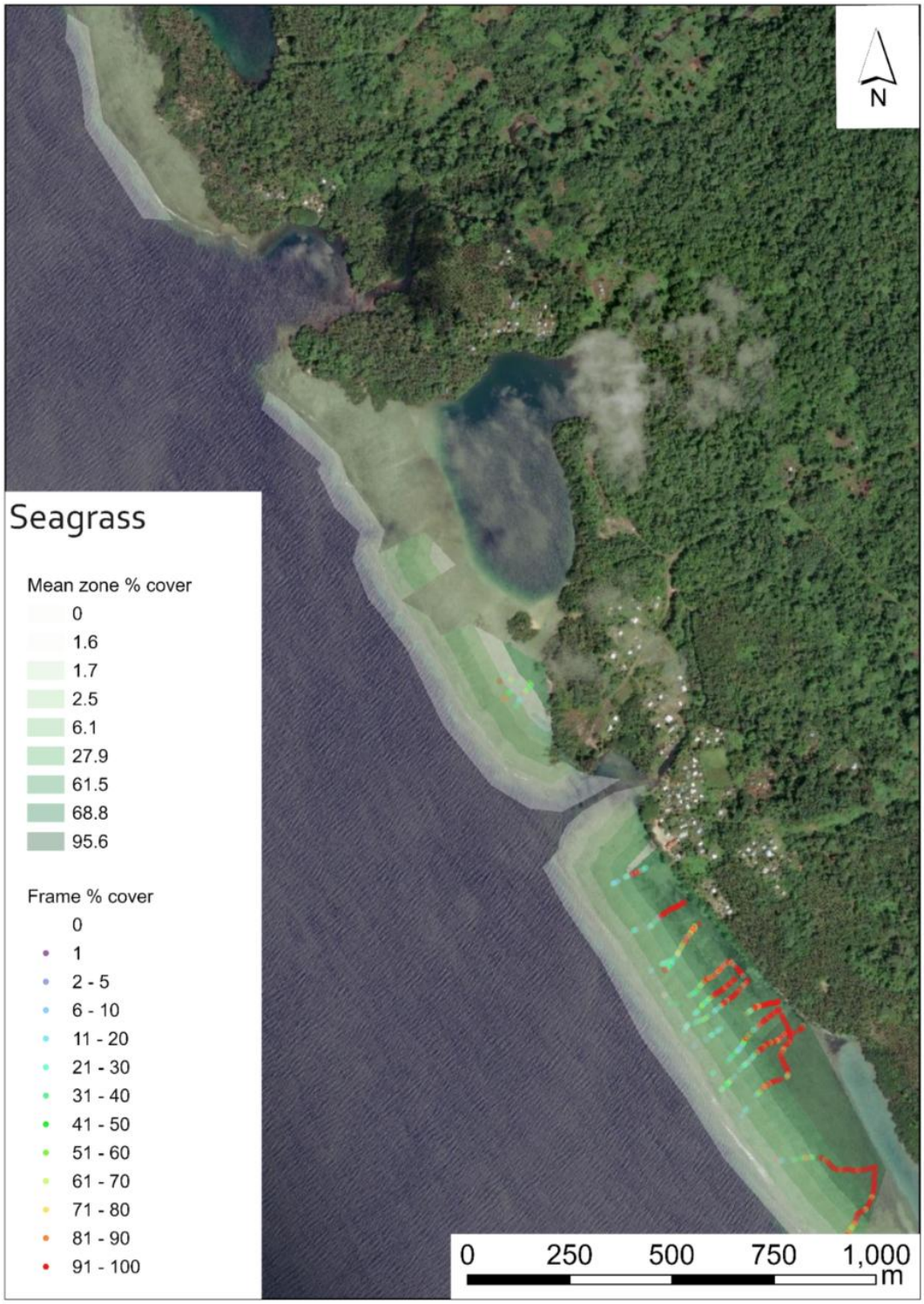

Figure 24. Percentage cover of *Seagrass* spp. derived from individual underwater video frames overlaid on the mean percentage cover predicted from classification and regression tree (CART) models.

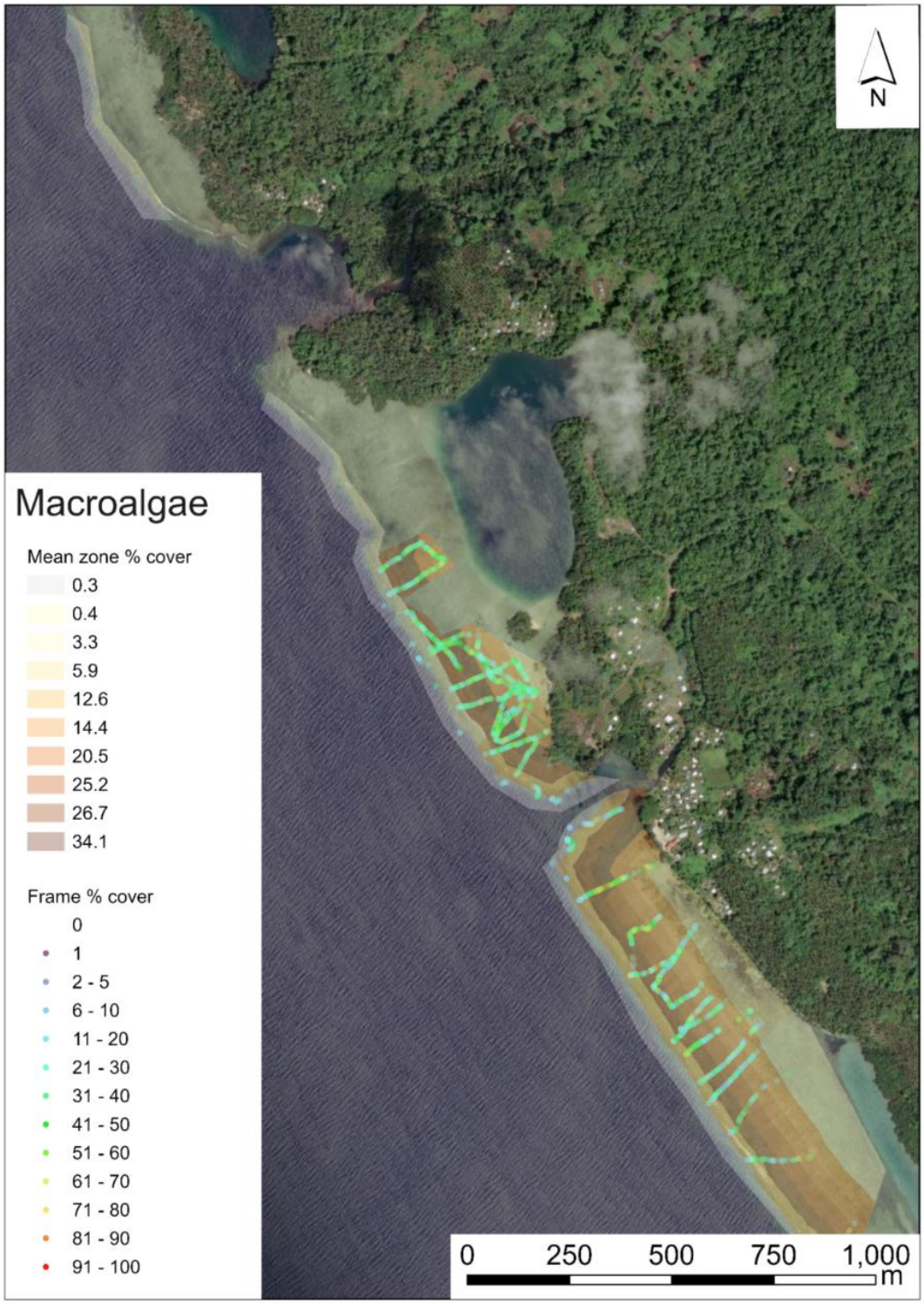

Figure 25. Percentage cover of macroalgae derived from individual underwater video frames overlaid on the mean percentage cover predicted from classification and regression tree (CART) model outputs.

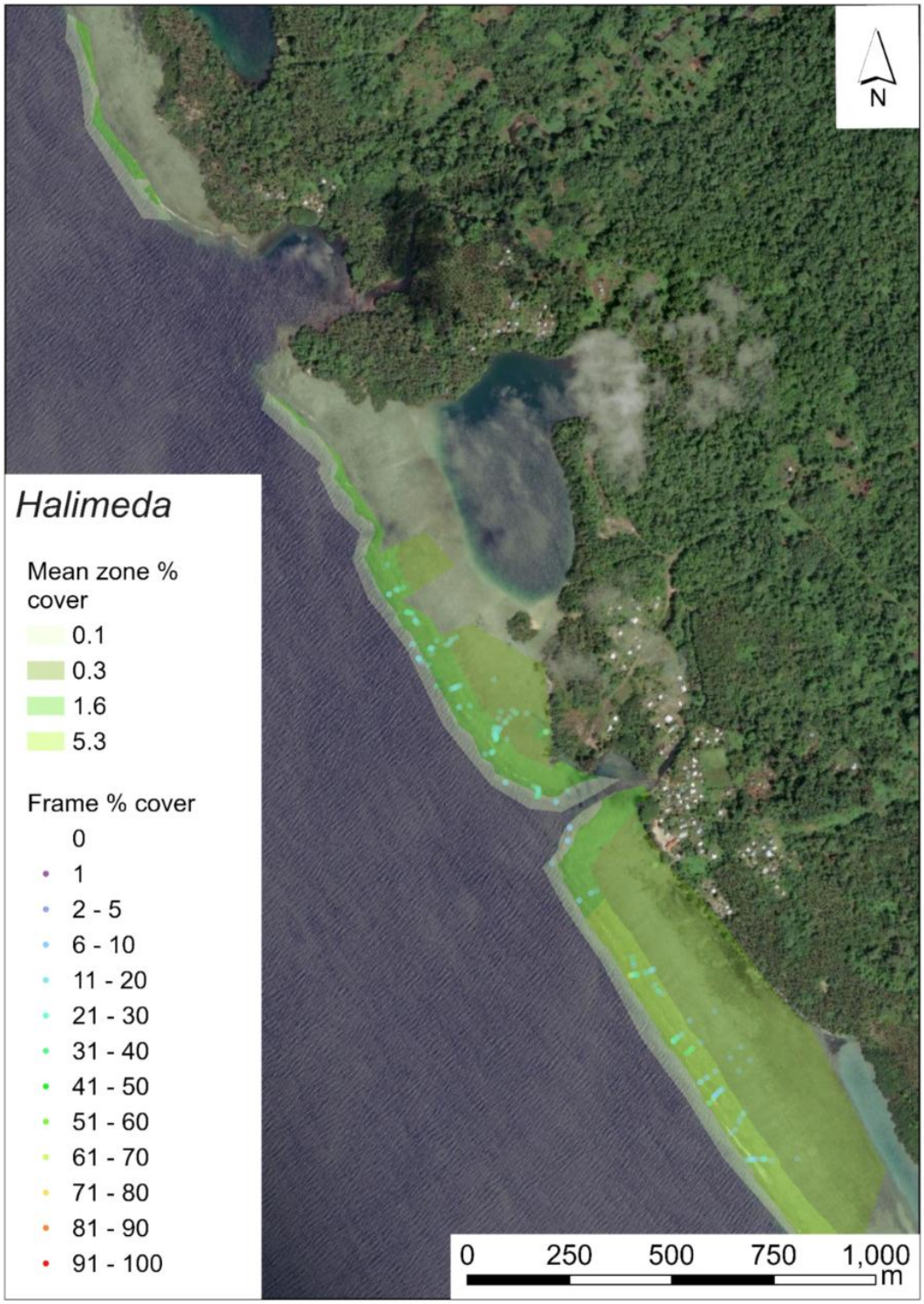

Figure 26. Percentage cover of *Halimeda* spp. derived from individual underwater video frames overlaid on the mean percentage cover predicted from the classification and regression tree (CART) model outputs

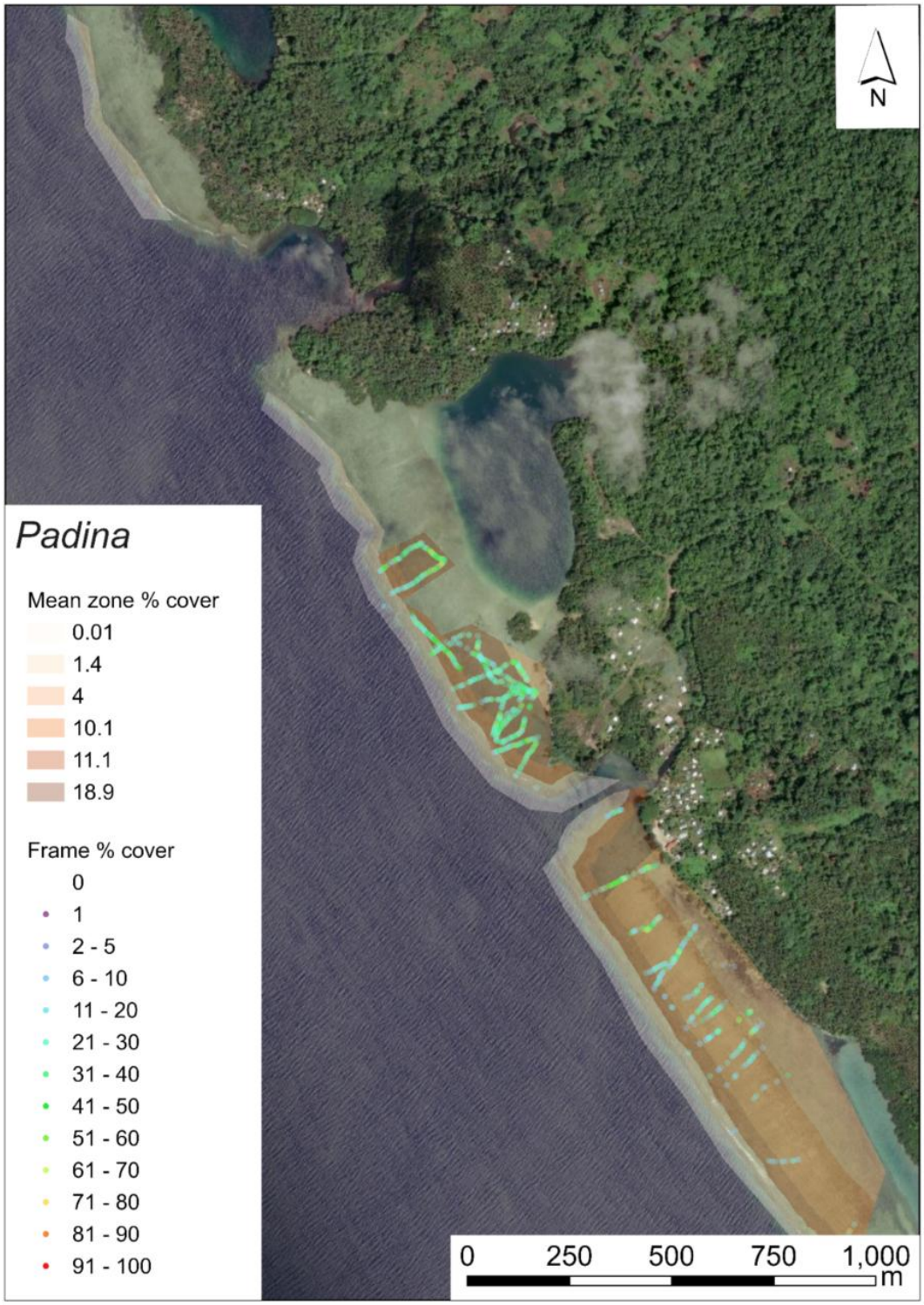

Figure 27. Percentage cover of *Padina* spp. derived from individual underwater video frames overlaid on the mean percentage cover predicted from classification and regression tree (CART) model outputs.

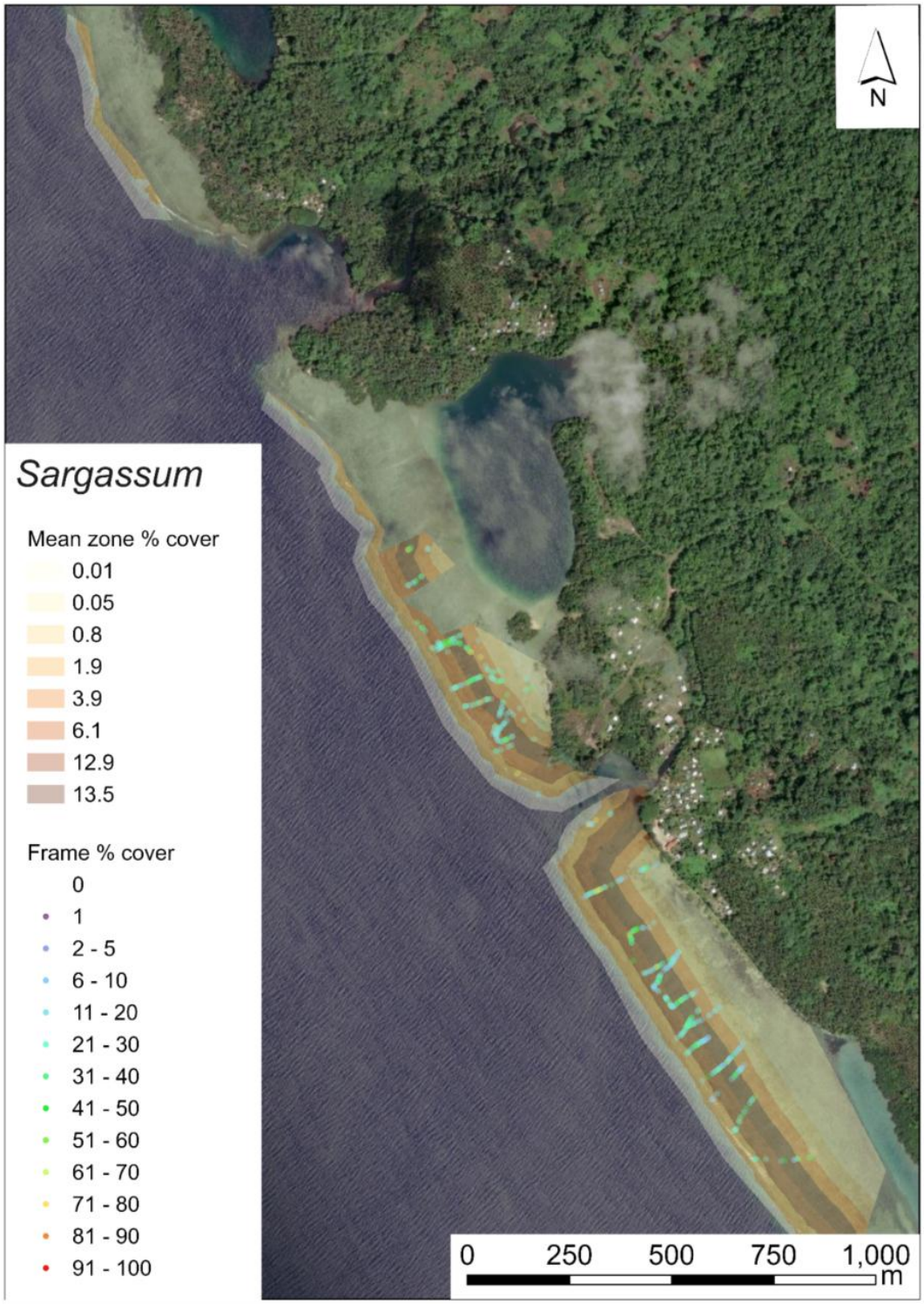

Figure 28. Percentage cover of *Sargassum* spp. derived from individual underwater video frames overlaid on the mean percentage cover predicted from a classification and regression tree (CART) model

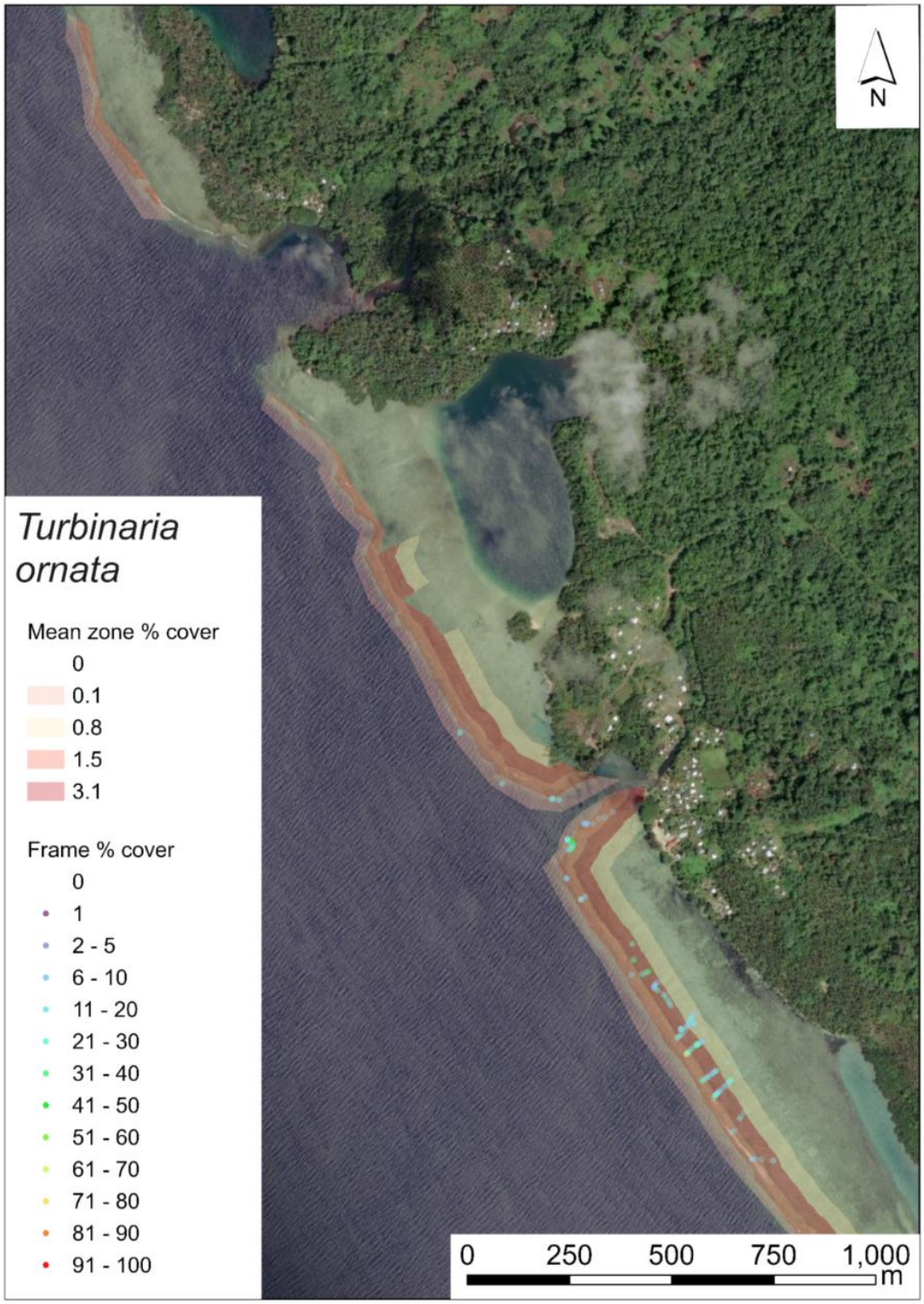

Figure 29. Percentage cover of *Turbinaria ornata* derived from individual underwater video frames overlaid on the mean percentage cover predicted from classification and regression tree (CART) models.

Consolidated coral rock

Cover of consolidated coral rock (Figure *30*) was highest within 55m of the reef crest, varied along the coast from 22 to 38%, and decreased inshore to 16% within 92m; 8% within 169m; 3% within 212m of the crest; and less than 1% between there and the shore. While still prevalent along the reef flat, coverage rapidly declined with increasing distance from the reef crest. Observed coral rock point densities closely align with areas of higher predicted cover, indicating a strong spatial agreement between modelled outputs and observed data points

Coral rubble

Cover of (Figure *31*) coral rubble ranged from 6 to 15% south of the river but varied between 27 and 40% north of the river. High cover points appeared consistently along the north reef, with few occurrences recorded on the southern reef flat.

Sand

Mean percentage cover of sand (Figure *32*) increased inshore from 1 to 3 % within 55m of the crest to 37% and 27% north and south of the river between 134 and 212m from the crest. Observed data points were consistent with these relationships, although sand south of the river was coarser in grain size and covered to a large extent by dense seagrass, which would reduce its apparent area considerably.

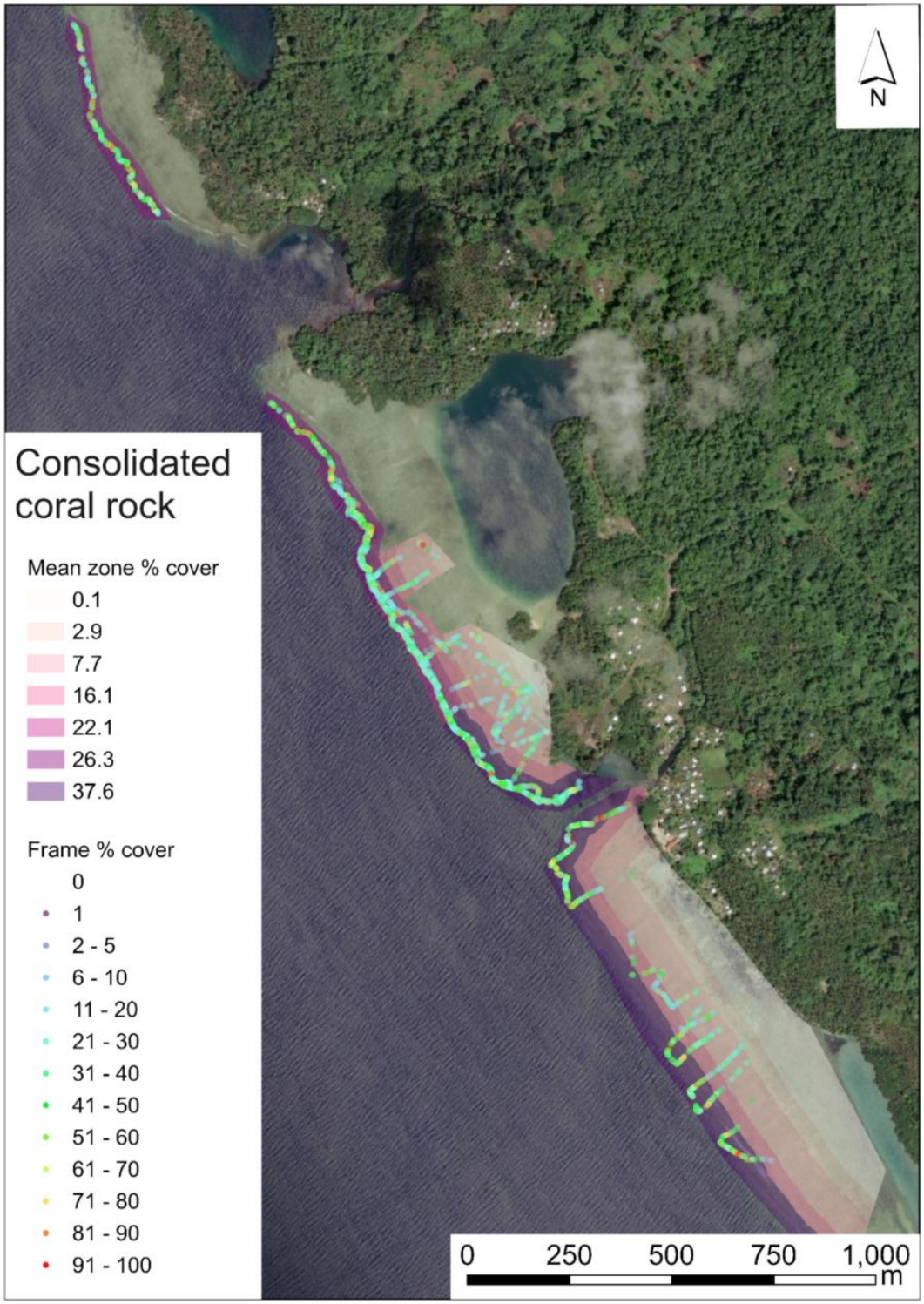

Figure 30. Percentage cover of consolidated coral rock derived from individual underwater video frames overlaid on the mean predicted percentage cover generated from classification and regression tree (CART) model outputs.

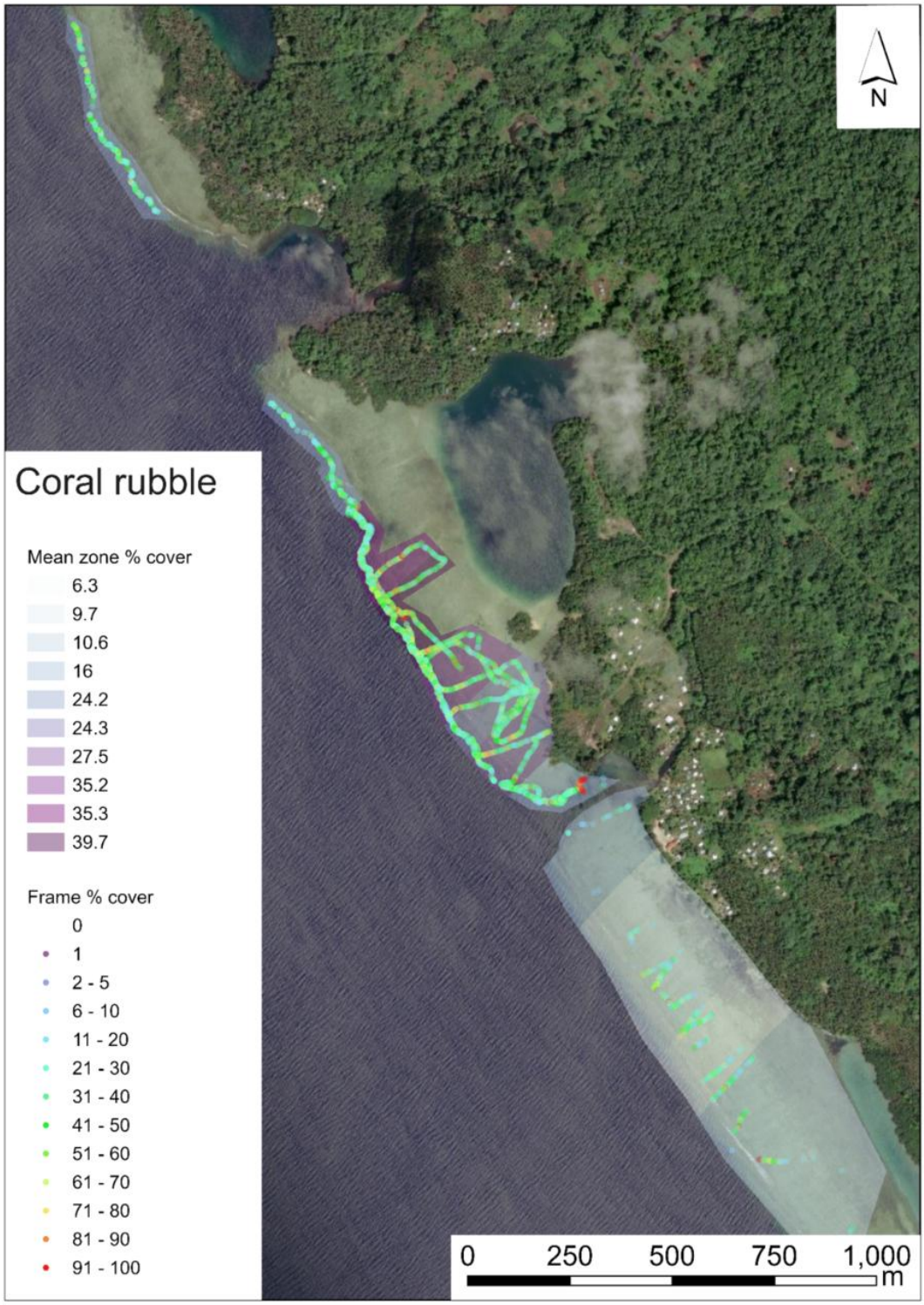

Figure 31. Percentage cover of coral rubble derived from individual underwater video frames overlaid on the mean predicted percentage cover generated from classification and regression tree (CART) model outputs.

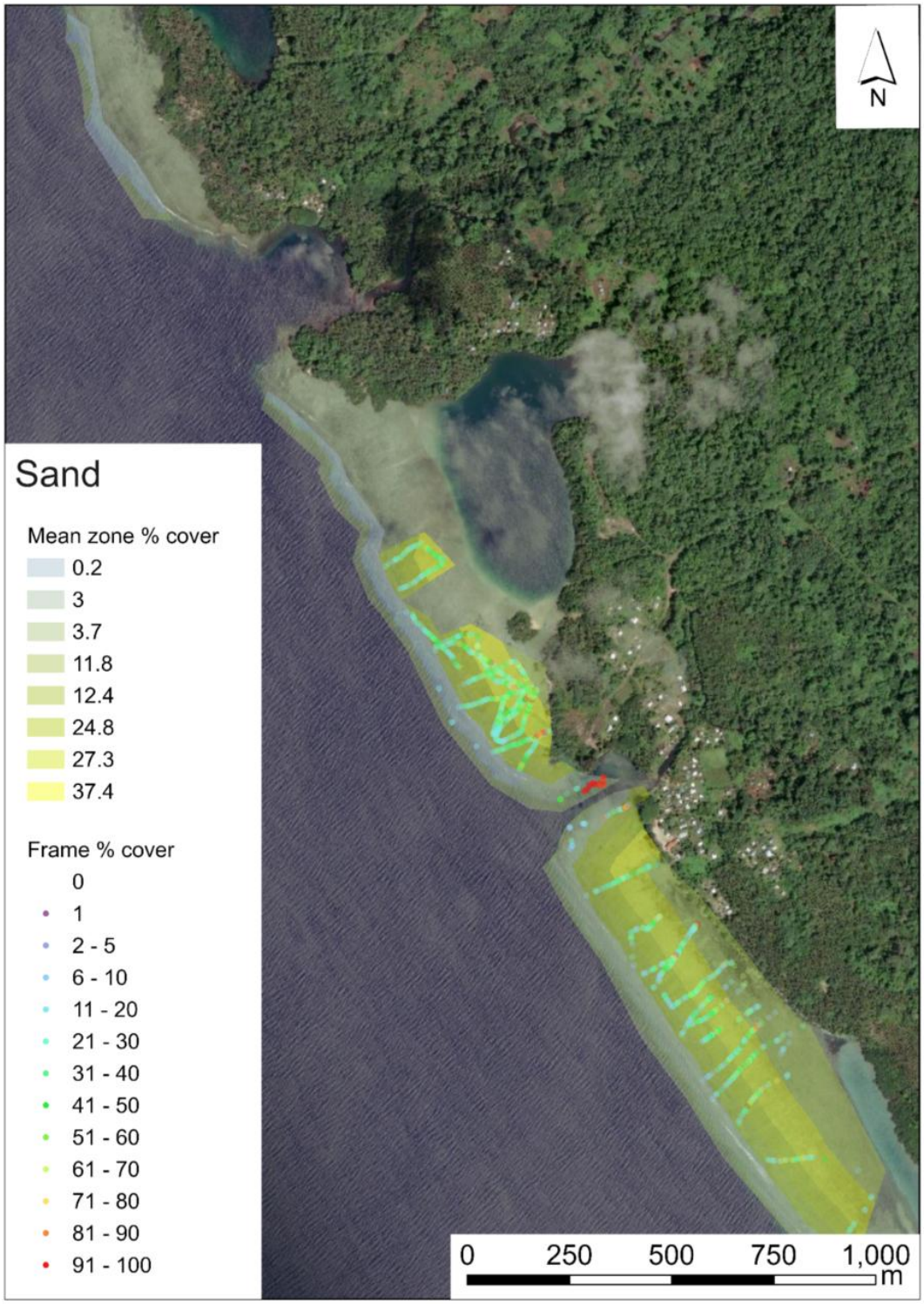

Figure 32. Percentage cover of sand derived from individual underwater video frames overlaid on the mean predicted percentage cover generated from classification and regression tree (CART) model outputs.

Multivariate composition

K-means multivariate clustering (ArcGIS Pro) of ten distinct benthic assemblages (Figure *33*) was derived from analyses of substrata and hard coral categories. Cluster membership was spatially dispersed across the entire study area, reflecting similarities in benthic composition rather than spatial adjacency. Clusters were observed along sections of the reef crest and adjacent to the river mouth, whereas others appeared infrequently and along the reef flat. The overall distribution of clusters illustrates compositional heterogeneity across both the north and south reef flats. Together, these patterns display clear spatial variability in benthic community composition, with distinct coral-dominated and substrate-influenced groupings evident across the study area.

Spatially constrained multivariate clustering (ArcGIS Pro) applied the spatial constraint that clusters comprise only spatially adjacent similar points. This was performed using percentage cover values of hard coral taxa and substrata (Figure *34*). Seventeen spatially contiguous clusters of different benthic assemblages were recognised across the north and south reef. In contrast to the clustering output shown in Figure *33*, cluster membership here formed contiguous areas rather than dispersed patches of similar points.

Distinct spatial segments stand out, with groups evident along the reef crest, river mouth region and southern reef flat transects. Along the northern reef, the section is characterised by relatively homogeneous zones, with a limited number of contiguous cluster types. In contrast, the southern reef flat showed far greater spatial heterogeneity, with more transitions between adjacent clusters.

Overall, the spatially constrained clustering revealed geographically coherent benthic assemblage zones, demonstrating that community composition follows a clear spatial structure across both reef flats.

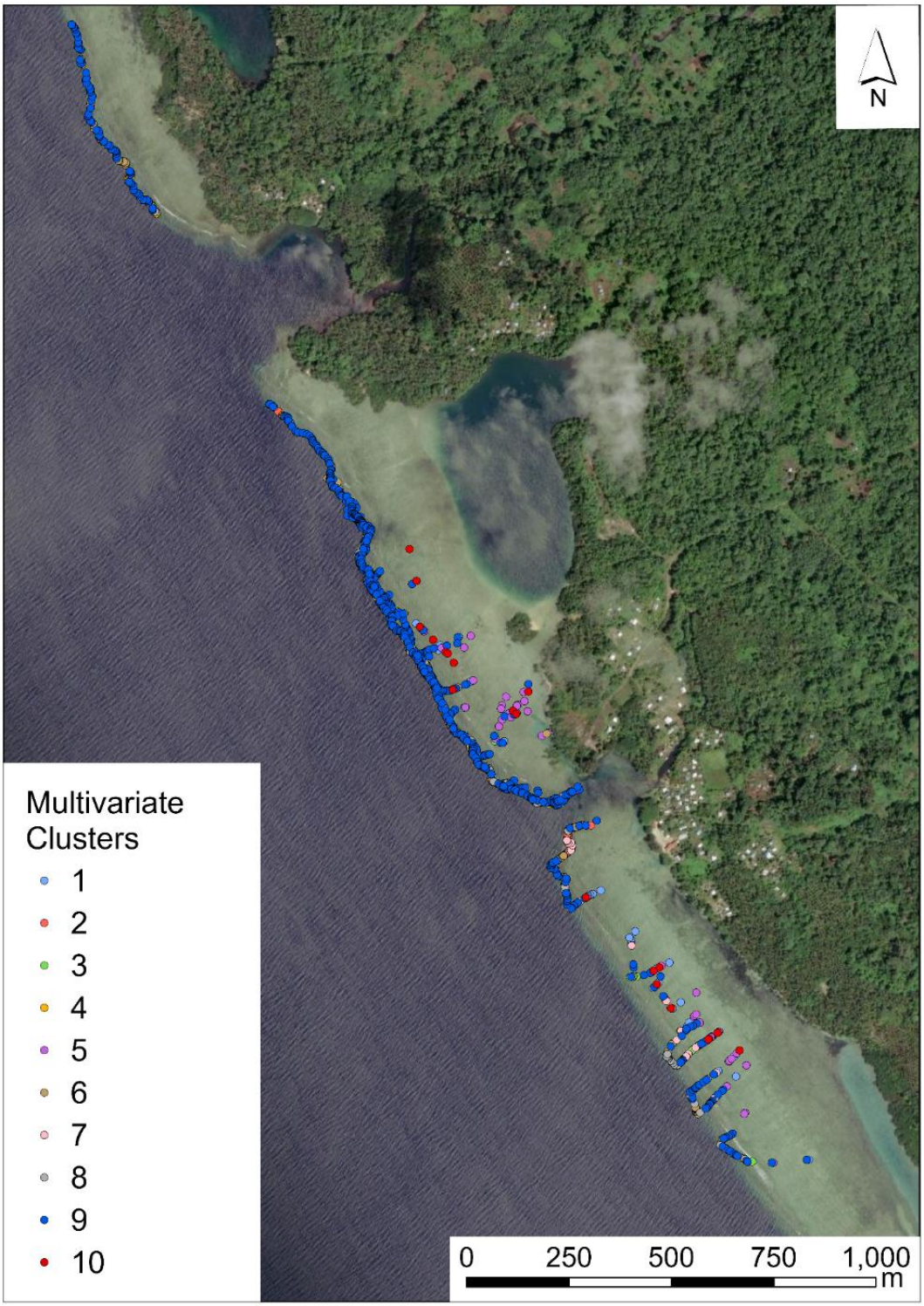

Figure 33. Unconstrained K-means multivariate clustering of benthic percentage cover across the Vavanga Village reef flats. Ten statistically distinct benthic assemblage clusters were derived based on the percentage cover of hard coral taxa and associated substrates

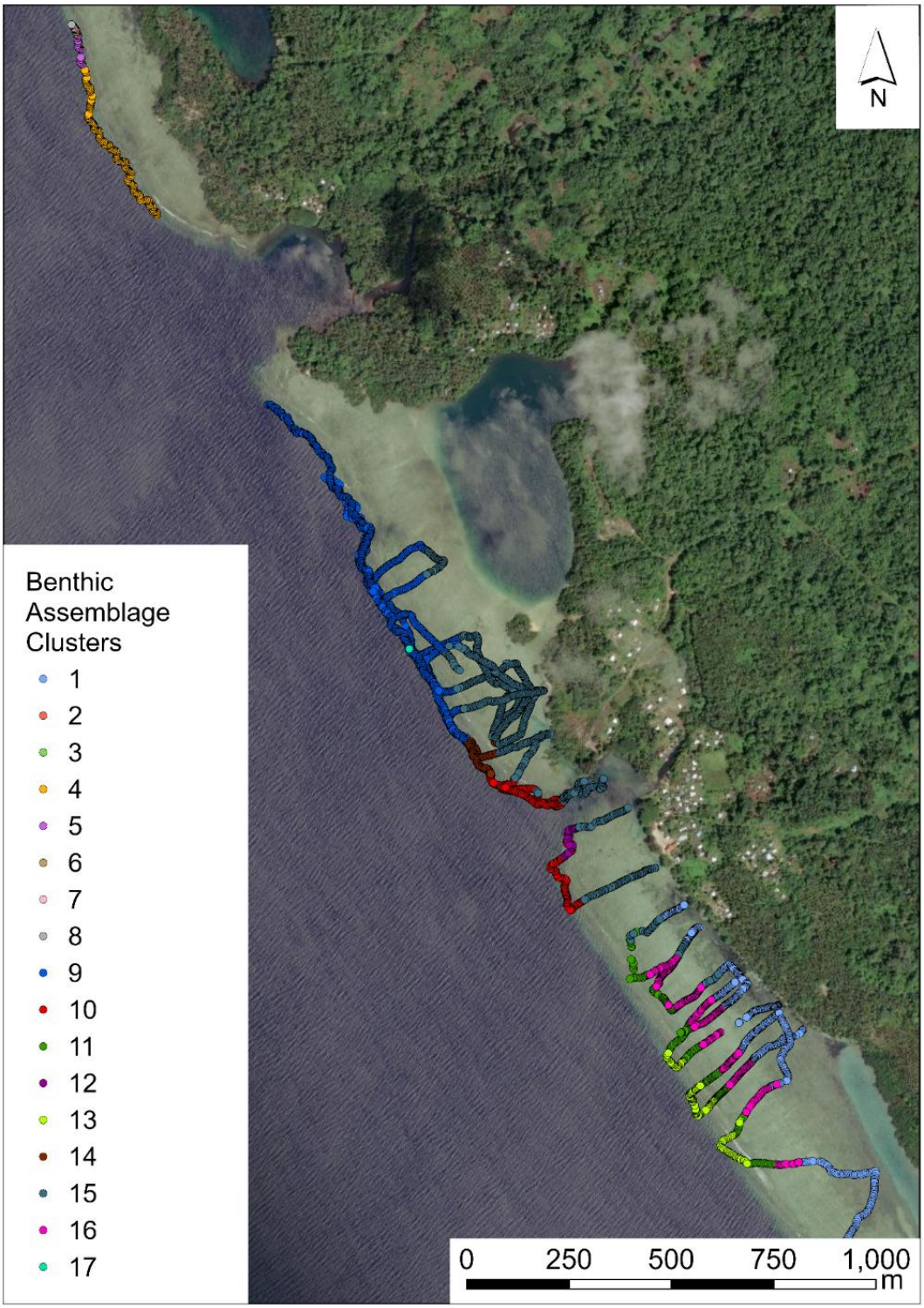

Figure 34. Spatially constrained multivariate clustering of benthic percentage cover across the Vavanga Village reef flats. Seventeen spatially contiguous benthic assemblage clusters were derived using the percentage cover of hard coral taxa and associated substrates

Spatial autocorrelation

Incremental spatial autocorrelation analysis (Figure *35*) revealed a significant positive spatial autocorrelation in the hard coral cover among points across all evaluated distance bands ($p < 0.001$). All Moran's I values were positive, illustrating a non-random spatial distribution of coral cover over the reef. Spatial autocorrelation increased across successive distance bands, reaching a maximum z-score at 121 m ($z = 245.18$). At this maximum distance, coral cover exhibited the strongest spatial structuring. As distance increased, z-scores gradually declined, while spatial autocorrelation remained statistically significant over all recorded distances. Figure *35* indicates that coral cover across the study area is spatially clustered and exhibits a clear scale-dependent pattern of aggregation. However, the values of Moran's I are so unusually high that they are likely to be influenced by the very high number of observations, their spatial proximity and non-random sampling.

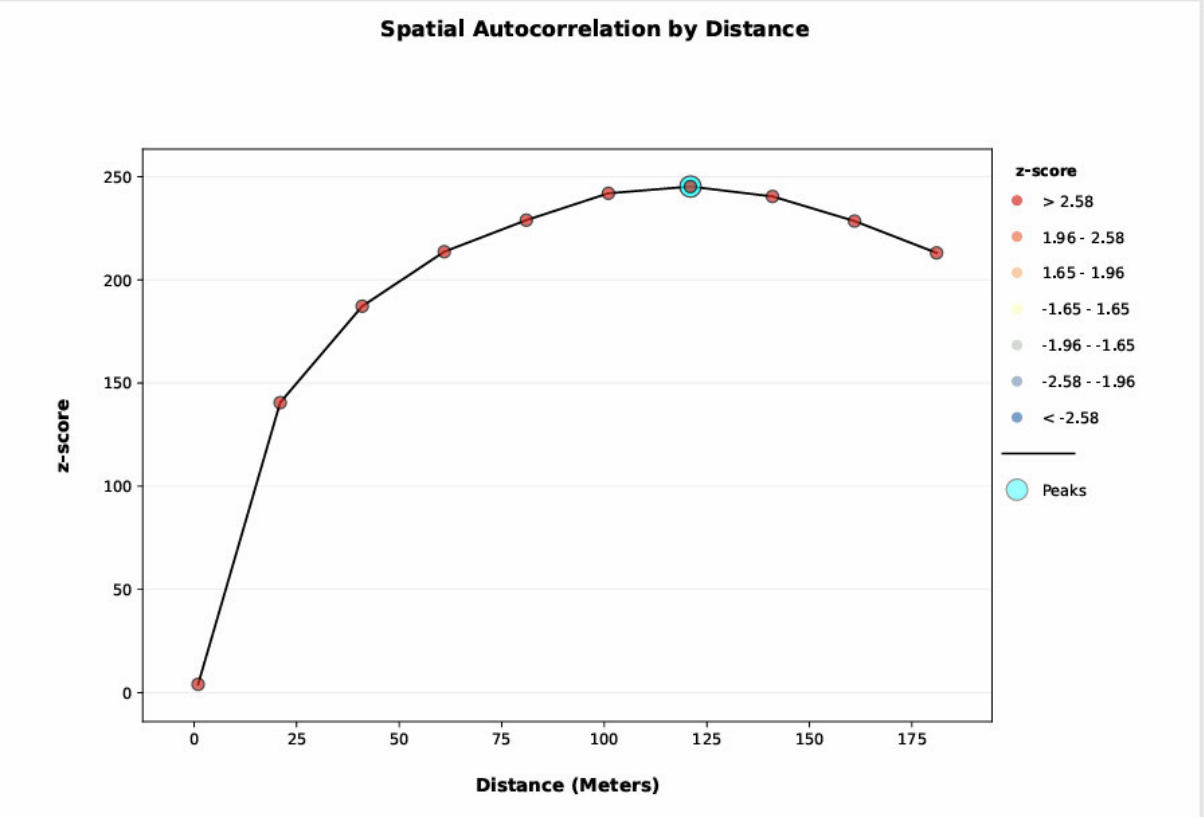

Figure 35. Incremental spatial autocorrelation (Moran's I) of mean hard coral percentage cover across increasing distance bands. Z-scores represent the strength of spatial clustering at each evaluated distance interval, with the peak value indicating the scale at which clustering is strongest.

4.4 ReefCloud results

In total, 195 survey images from the northern reef flat of Vavanga Village were manually uploaded into ReefCloud (Figure *36*). Images from the first transect on the 8th of December (T4) were manually classified, then further annotated by ReefCloud, which trained the model. Each frame contained a 4 x 4-point grid, with 12 classification points per image, yielding 2,340 potential annotation points over the dataset.

Of these, 74.2% of points were manually classified, with 9 of 12 points per frame annotated for training. The trained model subsequently classified 98.9% of the 9,750 total points across the entire survey, thereby substantially increasing the number of classified observations available for analysis.

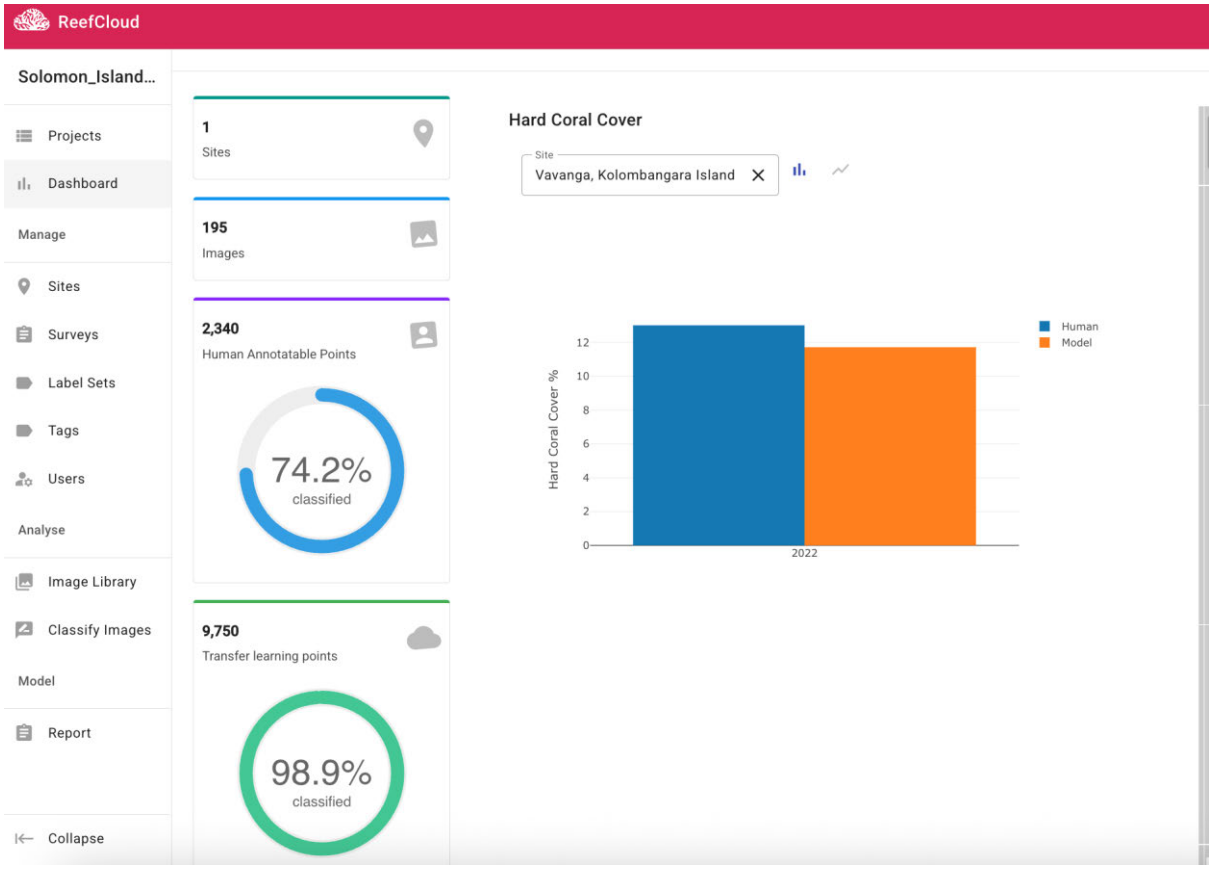

Figure 36**.** Summary of ReefCloud training dataset and model classification performance for 8th December (T4) reef flat transect.

Figure 37 shows model performance across multiple benthic categories using the F1 score. The overall F1 performance (~0.75) indicates a strong classification performance between manual and automated classifications across broad benthic categories. Abiotic substrata (sand, coral rubble, and consolidated coral rock), seagrass, and brown macroalgae each exhibited the highest F1 scores (>0.75), indicating strong agreement between manual and automated classifications.

Among hard coral forms, branching and foliose corals displayed moderate F1 performance, whereas sub-massive hard corals exhibited comparatively lower F1 scores, while sponge and turf algae showed lower F1 values than other categories. In contrast, the Unknown/Unidentifiable categories illustrated an almost-perfect F1 performance. Overall, broad structural categories achieved the highest F1 scores, while finer morphological distinctions achieved the lowest.

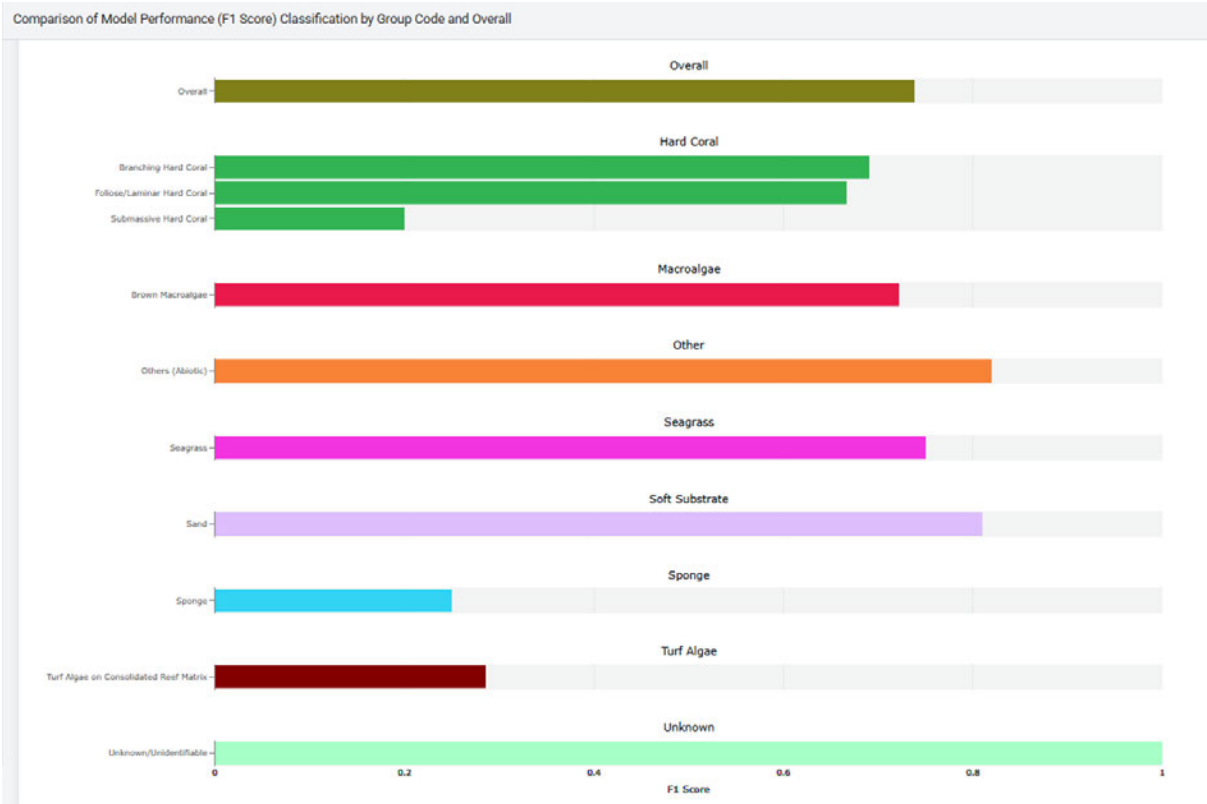

Figure 37. Comparison of model performance (F1 score) across benthic groups and overall classification accuracy.

Across all benthic categories, the differences between human and model-derived percentage cover estimates were low (Figure *38*). Many groups exhibited discrepancies of less than 2% in cover, indicating strong agreement between manual and machine annotations. Greater variation was observed in certain categories, such as brown macroalgae and various hard coral morphologies. This is expected for hard coral, as per Figure 37, which reflects the lower F1 score observed for this category.

Figure 38. Difference in survey percentage cover estimates between human and model classifications across benthic groups.

In addition, turf algae and sponges also showed moderate differences, most likely due to their visual similarity to nearby substrates and overlapping growth forms. Despite some discrepancies, no category observed showed extreme polarity in estimated cover, indicating that ReefCloud model outputs are robust for broad-scale benthic analysis.

After training the model using the manually annotated T4 transect, all other north reef flat transects were then uploaded to ReefCloud. While some frames deemed too blurred were removed, all other frames were classified exclusively without further manual correction. In total, 2,404 images were added for machine validation, with 120,200 possible points used by ReefCloud to train itself (Figure *39*).

The human-classified reference transects recorded a hard coral cover of 13.01%. In contrast, the model-derived classification across the entire northern reef flat dataset yielded a mean hard coral cover estimate of 16.22%, an increase of approximately 3.2 percentage points. This difference suggests a slight upward bias in model-derived hard coral estimates when extrapolated over the larger study area. Despite overall F1 performance and low

discrepancies in percentage cover during manual validation, this divergence reflects misclassifications rather than systematic error.

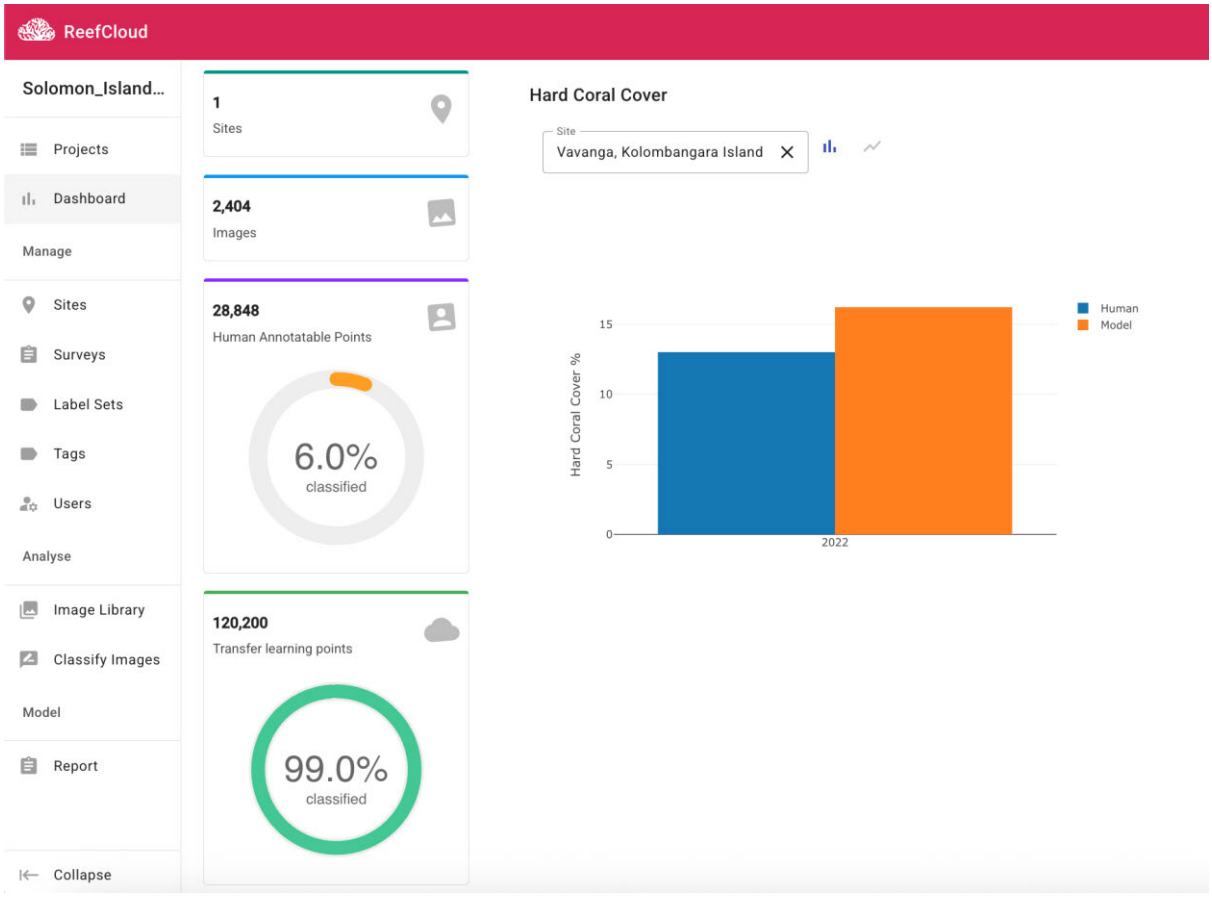

Figure 39. Hard coral percentage cover comparison between the human reference transects and model-derived estimates across all north reef flat transects.

As per Table 1, a frame-level comparison was performed between the manual presence and absence of corals against ReefCloud's model outputs. Across the total of 2,206 surveyed frames, 1,261 (57.2%) were identified as containing coral by both the manual and automated approaches (true positives). An additional 475 frames (21.5%) were identified as coral-absent (true negatives). ReefCloud independently classified 451 frames (20.4%) as containing coral, despite manual classification indicating its absence (false positives). In addition, only 19 frames (0.9%) were identified as coral absent, whereas manual observation recorded coral presence (false negatives). Overall, ReefCloud predicted the presence of coral in 1,712 frames and the absence of coral in 494 frames across the entire dataset.

Table 1. Confusion Matrix comparing frame-level coral presence between manual classification and ReefCloud

	Manual: Coral Present	**Manual: Coral Absent**	**Total**
ReefCloud: Coral Present	1261 (57.2%)	451 (20.4%)	1712
ReefCloud: Coral Absent	19 (0.9%)	475 (21.5%)	494
Total	1280	926	2206

Further performance metrics for frame-level coral detection are presented in Table *2*. ReefCloud displayed an overall classification accuracy of 79%, while the sensitivity (true positive rate) was significantly high (99%), suggesting that almost all manually identified coral-present frames were detected by the ReefCloud model. Specificity (true negative rate) was considerably lower (51%), indicating reduced agreement for frames absent from coral. Finally, precision (positive predicted value) was 74%, indicating that almost three-quarters of all frames predicted as coral-present by ReefCloud were confirmed by manual classification.

Table 2. Summary of frame-level model performance metrics comparing ReefCloud classification to manual coral presence/absence observations across 2,206 survey frames.

Accuracy	79%
Sensitivity (TPR)	99%
Specificity (TNR)	51%
Precision (PPV)	74%

Certain errors displayed by ReefCloud highlight instances where automated classifications differed from manual observations. With a precision score of 74%, the software incorrectly classified several benthic categories, with obvious substrata mislabelled (Figure *40*). As a result of these errors, human inspection remains crucial during the manual classification process, demonstrating that while automated classification offers numerous advantages, human inspection can improve results despite its time-intensive nature.

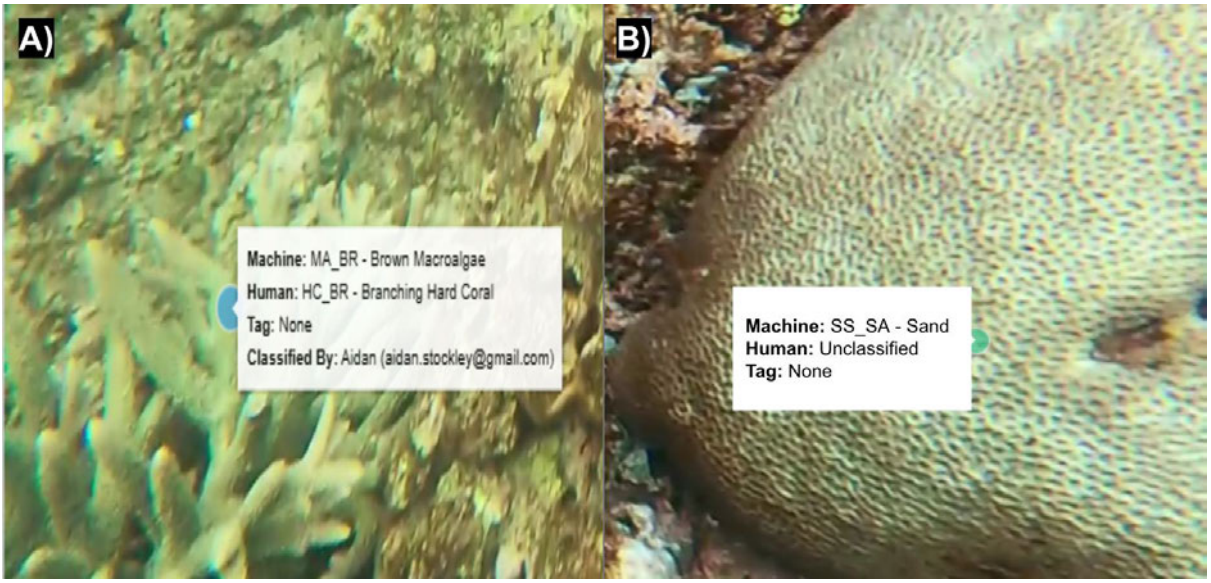

Figure 40. Examples of ReefCloud misclassifications. A) Branching hard coral incorrectly classified as brown macroalgae by ReefCloud. B) Favid hard coral incorrectly classified as sand. Both examples highlight the importance of manual verification during automated classifications.

5 Discussion

5.1 Benthic community patterns

5.1.1 Hard corals

Mapping spatial heterogeneity in benthic species assemblages and substrata on fringing reefs increases our understanding of how they may respond to environmental gradients (Legendre, 1993) and establishes baselines for measuring how they change over time.

Maps of the spatial distributions of *Acropora spp.* and *Pocillopora* spp. (Figure *20*, Figure *21*) show that these corals were largely restricted to the reef crest and to adjacent upper reef-slope and reef-flat zones. Both genera were among the most frequently observed hard corals but were largely absent from the inner reef flat in both the northern and southern regions, which were dominated by unconsolidated substrate and macroalgae, as previously described (Done, 1982*).*

This crest-focused distribution indicates strong environmental filtering linked to hydrodynamic exposure and substrate stability. Reef crest environments are characterised by intensive water movement and elevated wave energy, conditions that heavily favour structurally complex branching morphologies with high surface area and rapid growth rates.

Increased flushing further reduces sediment retention, thereby enhancing nutrient exchange and supporting taxa adapted to high-energy settings (Graham & Nash, 2012).

The limited occurrence of *Acropora* and *Pocillopora* within inshore reef zones suggests reduced tolerance to sediment retention and turbidity, commonly associated with low-energy depositional environments and to exposure to sun and freshwater during spring low tides. Whilst branching corals were observed near the river mouth, *Acropora* and *Pocillopora* were largely absent from sheltered inshore reef zones. These regions are characterised by reduced water movement and fine sedimentation, conditions unsuitable for branching corals due to their fine skeletal structure and limited capacity to shed accumulated sediments (Done, 1982; Fabricius, 2004*).* Branching corals serve as reliable indicators of high-energy crest zones across the Vavanga reef system, particularly along the northern reef crest (Done, 1982; Graham & Nash, 2012). Similar crest-restricted distributions of branching taxa have been extensively documented across Indo-Pacific fringing reef systems, where hydrodynamic exposure structures coral assemblages *(*Done, 1982*).*

The classification and regression tree analysis and simple observation of mapped data points support this interpretation, with the model identifying distance from the reef crest as the primary predictor of branching coral cover. Predicted cover sharply declined with increasing crest distance, whereas distance from Ghatere exerted a secondary influence within these crest-adjacent zones. The results reinforce the observed cross-reef zonation.

Contrasting with the distinct crest-restricted distribution of *Acropora* and *Pocillopora*, *Porites* displayed a broader spatial distribution (Figure 22). Massive *Porites* colonies, while prevalent along sections of the northern reef crest, extended well into the central reef flat in both the north and south reef regions. These zones lacked branching corals due to environmental stressors, which may limit the persistence of more delicate skeletal structures (Done, 1982; Fabricius, 2004*)*.

Massive *Porites* colonies are structurally more robust than branching taxa, allowing them to withstand increased sedimentation and the moderate hydrodynamic conditions on reef flats. These massive corals exhibit distinct hemispherical growth forms, which facilitate passive sediment shedding and reduce susceptibility to physical stress (Fabricius, 2004*)*. These traits allow colonies to persist beyond the high-energy crest zones and to expand across the intermediate reef flat.

Unlike *Acropora* and *Pocillopora*, *Porites* appear capable of persisting in areas susceptible to moderate sedimentation while maintaining structural stability across reef sections exposed to fluctuating hydrodynamic factors. Their massive morphology and strong attachment to consolidated substrata further enhance their resistance to both wave energy and sediment

deposition (Done, 1982; Fabricius, 2004*)*. This broader dispersal pattern coincides with observations from broader Indo-Pacific reef systems, where massive *Porites* species are documented across the reef crest, slope, and inner reef flat zones, suggesting greater tolerance to turbidity and sediment stress than branching taxa (Crabbe & Smith, 2005*)*.

Classification and regression tree analysis supports the broader ecological tolerance observed in *Porites*, as distance from the reef crest remained a key predictor, but with fewer abrupt declines than in branching taxa (Figure 16). Compared to *Acropora* and *Pocillopora*, the predicted *Porites* cover remained consistently moderate throughout the intermediate reef flat, suggesting a reduced sensitivity as crest distance increased. Distance along the reef also contributed to model splits, indicating other potential influences likely reflecting terrestrial and freshwater inputs. Despite this, hydrodynamic exposure remained a key driver.

Other hard corals, such as *Montipora*, had a comparatively patchy distribution and lower overall abundance (Figure *23*). *Montipora* was primarily concentrated along crest-adjacent zones, predominantly in the northern reef crest region. While certain colonies extended into intermediate reef-flat zones, no zonation patterns were evident (Done, 1982*)*. This spatial distribution suggests moderate tolerance to hydrodynamic exposure but limited competitive dominance throughout the reef flat. *Montipora* appears to serve a supplementary role in the crest and transition zones rather than as a dominant driver of zonation (Fabricius, 2004; Crabbe & Smith, 2005*)*.

Despite appearing alongside other branching taxa in high-energy zones, it is absent from sediment-dominated inshore regions. This reinforces the broader cross-reef structure observed within the Vavanga reef system. Overall, the distribution of branching, massive, and subordinate coral taxa shows a distinct morphological divide across the cross-reef gradient, driven by hydrodynamic energy and sedimentary influences (Done, 1982; Fabricius, 2004*)*.

5.1.2 Seagrass

A direct comparison between the northern and southern reef flats provides valuable insight into the response of benthic assemblages to differing environmental conditions within the same reef space. As explained by Martin (2024), both reef flats are influenced by riverine input; however, the southern reef flat more exposed to the currents of the open ocean but with wave energy attenuating progressively across the reef (Storlazzi et al., 2011*)*.

The northern reef flat is not only adjacent to the river mouth at Vavanga but also to several small creeks and mangroves and a large inshore lagoon that is likely to experience saline and freshwater conditions depending on rainfall. Substrata inshore on the northern flat is

often weathered limestone karst indicative of exposure. Finer grain sand and silt was also evident, and this area may have greater exposure to sedimentation and fluctuations in salinity and exposure during low tides compared with the southern reef flat (Fabricius, 2004; Ogston et al., 2004*)*. These contrasting settings provide a robust framework for interpreting divergence observed in biological communities and benthic structure across the two reef flats.

The distribution of seagrass demonstrates a significant spatial contrast between the two reefs. Mean percentage cover is substantially higher across the southern reef flat, peaking in the sheltered inshore regions. In contrast, the northern reef flat displays a considerably limited presence of seagrass. Total seagrass points appear to consistently cluster along the inner reef flat of the southern reef, aligning with areas of hydrodynamic exposure reduction and enhanced substrate stability (Duarte, 2002; Waycott et al., 2009*).*

The observed distribution is consistent with the cross-reef gradient in substrate composition and hydrodynamic exposure. Seagrass is largely absent from the exposed reef crest and the rubble-dominated zones on both reef flats, primarily occurring in low-energy environments where sediments accumulate over time (Duarte, 2002*).* Seagrass cover, however, is more extensive, dense and continuous across the southern reef flat, whereas the northern reef has a more fragmented coverage. This pattern may reflect greater fluvial influence and reduced water clarity near the river outlet, creeks, and the northern lagoon, with these conditions known to limit seagrass persistence under elevated turbidity levels (Orth et al., 2006*).*

CART analysis further supports the spatial distribution of seagrass (Figure 17) as distance from the reef crest was identified as the primary predictor, and predicted cover increased near inshore zones. Distance along the reef clearly separated the dense, wide bands of seagrass on the southern reef from the small areas to the north.

5.1.3 Macroalgae

Macroalgal assemblages were most abundant in mid to outer reef flat areas as opposed to inshore or reef crest areas. This suggests that macroalgae occupy a transitional ecological position, with peak abundance across intermediate reef-flat environments shaped by cross-reef gradients (McCook, 1999; Hughes et al., 2007*)*.

Macroalgae were most prevalent throughout comparatively exposed reef flat substrata. These areas provide macroalgae with sufficient light and stable attachment surfaces while being sheltered from extreme crest hydrodynamics and excessive inshore sediment

accumulation. Similar cross-reef sorting of substrates and sediments driven by wave attenuation has been observed on fringing reef flats, which supports macroalgal peaks in mid-reef zones compared to reef crests or inshore zones (Ogston et al., 2004; Storlazzi et al., 2011).

Halimeda exhibited a clearly structured distribution across the reef flat, with points concentrated along narrow bands adjacent to the reef crest, extending onto the reef slope (Figure *26*). This positioning suggests a preference for well-lit environments with moderate hydrodynamic exposure. Unlike inner reef-flat habitats, often characterised by fine sediment accumulation, the crest-slope transition zone provides firm substrates and rapid water movement, conditions considered favourable for calcifying macroalgae and consistent with reef-flat sediment transport processes in fringing reef systems (Ogston et al., 2004; Storlazzi et al., 2011*).*

As a calcifying green macroalga, *Halimeda* contributes substantially to carbonate sediment production in tropical reef systems. Its concentration along the reef slope suggests a functional role in sediment generation and reef-building dynamics (Hillis-Colinvaux, 1980). Classification and regression tree outputs, which identified cross-reef position as a dominant predictor of algal cover, were consistent with field observations along the reef slope (Appendix 6).

In contrast to the narrowly distributed *Halimeda*, the spatial coverage of *Padina* and *Sargassum* exhibited across the reef flat was much broader. Both genera occurred inshore of the reef crest, on the central reef flat, characterised by moderate levels of hydrodynamic exposure. Neither genus was strongly associated with the reef crest or the inner reef flat, suggesting a preference for transitional habitats that balance water movement, substrate stability and reduced sediment accumulation.

Sargassum displayed extensive mid-reef flat coverage across both reef flats, with significant coverage along the southern reef. *Padina* followed a similar distribution, though slightly patchier, with greater coverage along the northern reef flat. These spatial patterns suggest that both species are well adapted to moderately exposed reef-flat environments, particularly zones with high light availability and mitigated hydrodynamic stress. Their broader distribution relative to *Halimeda* indicates greater tolerance of sediment, exposure during low tides and high solar radiation, enabling persistence across a wide area of the reef flat.

Throughout Indo-Pacific reef systems, *Sargassum* and *Padina* are commonly associated with reef flat and back-reef environments, subject to seasonal variability and moderate hydrodynamic exposure (Hoey & Bellwood, 2009*)*. Patterns observed at Vavanga and

similar reef environments align with this, reinforcing the role of cross-reef hydrodynamic gradients in structuring macroalgae assemblages.

Classification and regression tree analyses support these patterns, with distance from the reef crest identified as the primary predictor for both *Padina* and *Sargassum* cover.

Turbinaria ornata had a more restricted distribution with points primarily concentrated along the crest-adjacent environment (Figure *29*). Mean cover formed narrow bands inside the reef crest, predominantly along the southern reef flat. This suggests that *Turbinaria ornata* exhibits a greater tolerance to hydrodynamic exposure compared to other macroalgae, while directly avoiding the high-energy reef crest zone. *Turbinaria ornata's* occurrence on outer reef-flat environments reflects morphological adaptation to moderate-to-high flow conditions. Comparable spatial patterns of *Turbinaria ornata* have been documented in Indo-Pacific reef systems, where settlement and persistence are each linked to substrate stability and exposure gradients (Stiger & Payri, 1999). Its limited inshore presence indicates a lower tolerance to sediment relative to *Padina* and *Sargassum* (Fabricius, 2004*).* Distance from the reef crest was identified as the primary predictor of *Turbinaria ornata* cover, and peak predicted values occurred directly within crest-adjacent distance classes.

5.1.4 Substrata

Proximity to the river mouth represents a significant environmental gradient, particularly due to its influence on substrate composition across both the northern and southern reef flat. The spatial distributions of consolidated coral rock, coral rubble, and sand may be related to cross-reef and along-reef differences in wave energy, freshwater, tidal currents, and atmospheric exposure.

Consolidated coral rock is common on the exposed reef crest, especially along the northern reef crest, though less common on the southern reef crest. Its presence in these high-energy zones reflects a sustained hydrodynamic exposure, where wave energy dissipation peaks *(*Storlazzi et al., 2011*)*. These consolidated substrata are optimal for calcifying encrusting coralline algae, which, though not readily identified in videos, provide stable attachment surfaces necessary for coral recruitment (Done, 1982).

Coral rubble is also strongly associated with the reef crest and adjacent zones, especially along the northern reef. In comparison, the southern reef flat had minimal coral rubble. This dominance of rubble across the northern reef may reflect increased physical disturbance, weathering and currents, especially during high rainfall or debris from offshore wave action (Ogston et al., 2004*)*. This pattern may also indicate various subtle differences in hydrodynamic processes between the north and south reef crest zones (Ogston et al., 2004; Storlazzi et al., 2011*)*.

Sandy substrata progressively increased away from the reef crest, dominating the inner reef flat regions of both the north and south reefs. Mean cover of sand was greatest in the sheltered inshore reef flat, where hydrodynamic energy is reduced, sediment retention increased, and moderate sand cover occurred near the river mouth. Sand is almost entirely absent from the exposed reef crest in both regions, reinforcing the opposite relationship between sediment accumulation and wave energy.

Similar patterns of sediment distribution have been observed across fringing reef flat environments, where wave-driven resuspension and transport processes arrange substrate types according to local energy regimes (Ogston et al., 2004*)*. Collectively, these patterns and substrates establish a distinctive cross-reef physical gradient, primarily influenced by hydrodynamic exposure. This structured gradient aligns with the observed patterns in hard coral assemblages. Crest-associated branching taxa correspond with consolidated substrates, whereas sand-dominated inner reef flats support reduced coral abundance (Done, 1982; Fabricius, 2004).

Distance from the reef crest was the primary predictor of both consolidated coral rock and sand distribution. Consolidated coral rock sharply declined as crest distance increased, whereas sand cover progressively increased across inshore zones. Distance along the reef further refined model splits, possibly reflecting local fluvial effects within an otherwise crest-driven system.

The spatially explicit outputs from this study provide an important ecological baseline for the northern and southern reef flats of Vavanga, addressing the significant gap in long-term monitoring (Rivera-Sosa et al., 2025*).* These reefs remain under-represented in sustained bleaching and habitat condition datasets, in contrast to larger barrier reef systems that attract more attention (Mellin et al., 2020). Establishing fine-scale benthic composition maps enables future comparisons of coral cover, structural complexity, and substrata in response to local and global disturbances.

Incremental spatial autocorrelation analysis showed significant positive clustering at all distances, peaking at approximately 120m. In addition, multivariate clustering demonstrated that benthic communities formed distinct assemblages across and along the fringing reef, while spatially constrained clustering showed assemblages occurring as geographically coherent zones rather than isolated patches, indicating spatial organisation across environmental gradients.

5.2 Human-AI hybrid classification and ReefCloud

ReefCloud was used in this thesis as a supplementary classification tool to further explore image-based classification using semi-automated technology. Once appropriately trained, it can cover large-scale areas; however, the initial setup phase is time-consuming. Preparation and input of manually classified images for AI was time-intensive and required careful training before the AI could differentiate corals from substrata. Ensuring benthic classes were accurately defined and consistent across existing manually classified imagery, while tackling upload constraints, was crucial to the reliability of ReefCloud's output.

Setup demands demonstrated an important trade-off directly tied to machine learning algorithms. Despite automated machinery being able to greatly reduce long-term effort, the upfront investment of required calibration is substantial to achieve any meaningful result. As a result, the use of ReefCloud was helpful but treated as a complementary tool rather than a full replacement for manual classification. This reinforces the importance of human oversight during required training phases when applying AI-assisted tools to approach complex reef flat environments.

Across all benthic categories, model performance varied considerably, with higher F1 scores observed for broader structural groups, including consolidated substrata, sand, seagrass, and brown macroalgae. As each category has a distinctive visual signature in reef imagery, the model consistently differentiated among them. In comparison, certain hard coral morphologies, turf algae, and sponges had lower F1 scores, reflecting their visual complexity. Overlapping growth forms and distinct morphological differences, therefore, make automated classification far more challenging. These findings highlight the significant limitations machine learning faces when attempting to differentiate fine-scale benthic categories from imagery (González-Rivero et al., 2020).

Further frame-level performance metrics illustrate both strengths and limitations in ReefCloud's classification approach. Overall accuracy of the model was 79%, with remarkably high sensitivity (99%), demonstrating that almost all manually identified coral-present frames were correctly detected by the automated classification tool. Despite this success, specificity was low (51%), indicating that ReefCloud occasionally classified corals in frames marked absent by manual observations.

This tendency towards false positives is further reflected in the distinct overestimation of coral cover across the entire dataset, with model-derived coral cover 3.2 percentage points higher than the manually classified reference transect. Despite this bias, the dataset showed an extremely low rate of false negatives, suggesting that ReefCloud almost never failed to identify coral when present. This may prove advantageous for broad-scale reef monitoring

applications, where failing to detect coral habitats would ultimately be more problematic than moderate overestimation, if outputs remain subject to manual review (González-Rivero et al., 2020).

5.3 Socio-ecological context

5.3.1 Socio-economic importance and fisheries

Vavanga's fringing reef is highly important to the local community, supporting fisheries and cultural practices, providing protection for shorelines, enhancing food security, and potentially supporting a range of other uses, such as tourism and aquaculture (Moberg & Folke, 1999; Schwarz et al., 2011*).* These reefs are a vital source of protein and subsistence income, providing opportunities in a region where alternative livelihoods remain scarce (Farmery et al., 2020*).* As a result, cross-reef gradients documented at Vavanga reflect not only spatial patterns but also the ecological foundation on which community resilience depends.

For example, the different sand, seagrass, and macroalgal assemblages on the sheltered reef flats and the structurally complex corals on the reef crest and slope have implications for fish assemblages and harvesting pressures. Branching coral habitats are notably structurally complex, typically support high biodiversity and fish biomass and include reef-associated species targeted by small-scale fisheries (Graham & Nash, 2012).

Any decline in these crest-proximal habitats, driven by factors such as sediment, hydrodynamic stress, rainfall and high temperatures, could ultimately undermine food security in island nations. As Pacific coastal communities heavily rely on reef fisheries for daily protein intake, ensuring spatially heterogeneous reef systems is essential to long-term socio-ecological resilience. Within the Solomon Islands specifically, documented responses to declining coastal fisheries include intensified effort and shifts in targeting, increasing pressure on nearshore reef zones, while reinforcing vulnerability where food and income are connected to subsistence fishing *(*Albert et al., 2015b).

5.3.2 Land-sea interactions and sediment impacts

The Solomon Islands operates under established customary marine tenure systems, with reef zones traditionally governed through local stewardship and community-led decision-making (Cinner & Aswani, 2007*).* Within this context, the benthic composition maps for Vavanga provide value beyond ecological description. By identifying sediment-dominated

zones, structurally complex coral habitats and potentially vulnerable locations, these findings may help local communities manage and sustain their local marine resources and biodiversity.

Image-based reef mapping functions not only as a complementary research tool but also as a key spatial decision-support resource. It serves as a bridge linking ecological data and community-scale governance. By clearly identifying significant biotic and abiotic regions, these outputs can enhance participatory GIS initiatives and community-led monitoring. This can strengthen adaptive management practices for both scientific observation and customary knowledge systems *(*Obura et al., 2019*).*

Substrate composition, light availability, productivity, diversity and coral recruitment can be severely impacted by catchment-derived sediment and nutrient inputs (Carlson et al., 2019*).* In the Solomon Islands, logging and land-clearing activities within coastal catchments have been shown to increase sediment export to adjacent reef systems, intensifying pressure on nearshore fringing reefs (Albert et al., 2015a*).* Within small island contexts, steep catchments and high rainfall variability both intensify these processes, leading to rapid transport of terrestrial runoff into proximal reef flats.

Persistent sedimentation is detrimental to branching and sediment-sensitive coral species, reducing recruitment success and survivorship (Fabricius, 2004*)*. Over time, this selective process can begin to favour sediment-tolerant morphologies and more stress-resilient assemblages, reinforcing structural shifts. These findings reinforce the importance of integrated land-sea management approaches in reef-flat environments proximal to river systems (Carlson et al., 2019*)*.

Monitoring efforts that focus solely on marine drivers may overlook additional terrestrial pressures, particularly those with a gradual, cumulative influence on reef condition. Sediment delivery from catchments may not only cause rapid, visible degradation but also alter substrate composition, reduce coral recruitment, and alter overall benthic communities over time (Fabricius, 2004*)*. Recognising these land-sea connections is essential for accurately understanding reef health in nearshore environments influenced by fluvial processes.

From a management perspective, spatially explicit benthic mapping can help identify zones susceptible to sediment stress and habitat transition. By delineating sediment-dominated inshore zones and structurally complex reef crests, model outputs from this research provide a solid spatial basis for connecting upstream land-use processes with downstream reef conditions. Vavanga Village's reef flat illustrates how local-scale ecological mapping can contribute to broader ecosystem-based management strategies. These approaches explicitly

recognise connectedness between processes of catchment and coral reef resilience (Obura et al., 2019).

5.3.3 Climate change and future vulnerability

Across the globe, coral reefs are experiencing the impacts of increasing thermal stress, ocean acidification, and alterations in disturbance frequency (Hughes et al., 2017). Notably, small island developing states are disproportionally vulnerable to these impacts (Moberg & Folke, 1999). Fringing reef systems, specifically those at Vavanga, face climate-driven stressors alongside local pressures, influencing benthic composition, structural complexity, and long-term resilience. Mass coral bleaching events have become considerably more frequent across the Pacific region, significantly reducing live coral cover, while altering community composition (Heron et al., 2016; Hughes et al., 2018).

While often dominant in structurally complex coral-reef environments, branching and fast-growing coral taxa are among the most sensitive to prolonged periods of heat stress. Repeated bleaching events may therefore disproportionately affect these crest-associated habitats at Vavanga, which were identified as both ecologically and socio-economically significant (Hughes et al., 2018). Ocean acidification places additional stress on shallow, high-energy reef flat environments by reducing calcification rates and weakening reef framework integrity (Speers et al., 2016). In combination with global warming-driven bleaching, these processes may progressively erode the structural complexity of crest-associated habitats identified at Vavanga.

Beyond the direct impacts of warming temperatures and ocean acidification, climate stress interacts with existing local pressures. Chronic sediment exposure may worsen coral health prior to bleaching events, significantly reducing thermal stress resistance and restricting potential recovery for taxa within inshore zones (Carlson et al., 2019). Furthermore, sediment stress can greatly impair physiological function, while lowering resistance thresholds prior to the occurrence of thermal anomalies (Fabricius, 2004). As such, spatial gradients observed at Vavanga may illustrate not only modern zonation patterns but also altered vulnerability levels under potential future climate scenarios, where both local and global stressors converge.

In large oceanic states such as the Solomon Islands, where coastal communities are largely dependent on reef fisheries and shoreline protection, climate-driven reef degradation carries significant socio-economic implications (Jupiter et al., 2018; Moberg & Folke, 1999). Spatially explicit benthic mapping, in turn, provides an essential ecological baseline against which future climate-driven shifts in habitat composition and structural complexity can be

assessed, addressing the broader gap in long-term monitoring of fringing reef systems (Mellin et al., 2020*).*

In data-limited Pacific contexts such as the Solomon Islands, where logistical and financial constraints greatly restrict sustained monitoring programmes, the development and implementation of a spatially explicit baseline dataset is highly significant (Obura et al., 2019). These outputs establish a reference condition against which future surveys can assess shifts in coral cover, substrate composition, and structural complexity. While this study merely represents a single temporal snapshot of the Vavanga reef flat, the reliable, repeatable workflow and spatially continuous outputs provide a strong basis for future long-term monitoring in fringing reef systems, which have historically received limited scientific attention (Mellin et al., 2020).

These findings systematically demonstrate the value of integrating RPA-derived FMV, image-based classification and GIS modelling in fringing reef environments. The workflow in this study captures spatial continuity across broad areas (English et al., 1997). Incorporating semi-automated classification via ReefCloud, in combination with CART modelling and cluster analyses, illustrates the potential of digital tools to enhance efficiency while maintaining analytical robustness. This approach is both repeatable and scalable, providing a practical framework for community-based monitoring, particularly in regions with logistical constraints *(*González-Rivero et al., 2020).

As the dataset captures only a single point in time, it omits seasonal variability and post-disturbance recovery dynamics. Image resolution, water clarity, and observer verification thresholds each influence overall accuracy (Roelfsema et al., 2018). Environmental drivers such as turbidity, sediments, currents, rainfall, flood plumes and nutrients were not quantified in this study. In addition, while CART and clustering patterns help enhance pattern detection, they rely heavily on the quality of the input data (González-Rivero et al., 202*0*). Collectively, these limitations highlight the need for temporal replication and the integration of direct environmental measurements to enhance causal interpretation of spatial patterns.

When conducting future research, focus should be placed on temporal replication of the Vavanga reef flat survey, as this can detect shifts in benthic composition after subsequent thermal anomalies, weather phenomena, or potential changes in catchment land use (Heron et al., 2016). Pairing spatial benthic mapping with water quality monitoring, hydrodynamic models and fisheries assessments would enhance understanding of ridge-to-reef connectivity and resiliency in socio-ecological systems (Carlson et al., 2019). Integrating participatory GIS with community-led monitoring would also support local knowledge of these areas (Obura et al., 2019). Together, this framework supports a scalable foundation

for connecting ecosystem-based monitoring with adaptive management in nearshore reef environments.

5.4 Limitations of the study

This study was designed to evaluate image-based reef-monitoring approaches in shallow fringing-reef environments, with a specific focus on the fringing reef at Vavanga Village, Solomon Islands. The scope of this study was intentionally limited to shallow reef-flat habitats, which could be effectively surveyed using RPAs and snorkel-based underwater video methods. Additional reef zones, such as fore reef slopes and deeper reef environments, were intentionally excluded from the analysis.

This study focused primarily on achieving spatial continuity and high repeatability rather than rapid data extraction. As a result, the workflow required substantial post-processing effort to manually classify and relied on high-quality imagery for accurate benthic classification. Image-based approaches, however, are still affected by environmental conditions such as turbidity, variable lighting and motion blur, which can reduce classification confidence.

Manual classification was performed with caution and formed the foundation of the analysis. Despite undergoing a secondary review and utilising reference datasets, interpretative uncertainty remains. ReefCloud was applied in an exploratory capacity, providing confidence and additional insight into the potential role of semi-automated classification. Due to training requirements and overall constraints, ReefCloud was treated as a complementary tool rather than a complete replacement for manual classification.

This study provides a reproducible framework for spatially continuous fringing reef monitoring in both remote and under-represented regions. The workflow demonstrates how image-based methods can be applied in shallow reef environments, while highlighting the trade-offs among spatial coverage, accuracy and overall processing effort. This approach offers a practical foundation for both future fringing reef monitoring and the development of innovative spatially explicit survey and analysis methods.

Although image-based approaches require significant post-processing effort, the trade-off between overall processing time and improved spatial resolution was considered highly acceptable. The ability to assess benthic composition across the entire Vavanga reef flat provides a significant methodological advantage for examining environments impacted by

land-sea interactions, where spatial gradients of patchiness are ecologically significant (Mumby et al., 2003; Andréfouët & Bionaz, 2021*).*

Fine-scale assessments based on discrete sampling points may fail to capture the full extent of spatial heterogeneity and spatial structure, particularly where ecological patterns exhibit spatial autocorrelation (Legendre, 1993*).* The workflow adopted in this study ultimately prioritised repeatability and true spatial coverage over rapid data extraction. This approach further aligns with the broader aim of improving reef flat monitoring frameworks and assessment technologies across coral reef systems, including underrepresented and remote locations (Obura et al., 2019*).*

Traditional monitoring methods used in coral reef studies tend to rely on point-based sampling, such as transects and quadrats (Hill & Wilkinson, 2004*).* Despite each method being recommended for fine-scale ecological surveys, both may be limited in their ability to capture spatial structure at broader ecological scales where patterns may appear spatially autocorrelated (Legendre, 1993*).* Surveys following these approaches assume that sampled points represent the surrounding habitat; however, they fail to account for environments with strong gradients over short distances, notably reef flats adjacent to river mouths influenced by land-based inputs (Carlson et al., 2019*).*

In contrast, image-based workflows and the continuous spatial coverage they provide allow distinct benthic patterns to be assessed across the entire reef flat (Mumby et al., 2003). This distinction is particularly relevant in shallow reef flat environments such as Vavanga Village, where factors such as sedimentation and turbidity can vary over relatively short distances, influencing benthic assemblages (Jones et al., 2021*).* Preserving spatial continuity is crucial, as it ensures that continuous sampling will significantly reduce the risk of omitting fine-scale transitions or locally distinct assemblages that may be overlooked with traditional random sampling or under evenly spaced transects *(*Legendre, 1993*).* While not replacing conventional sampling methods, continuous spatial approaches should be seen as complementary, providing a broader spatial context for fine-scale ecological observations, pattern recognition and strengthening monitoring frameworks *(*Obura et al., 2019*).*

Troubleshooting was one of the more time-consuming constraints in the workflow. Processing FMV and underwater scooter footage was time-intensive, as each transect required careful frame-by-frame inspection to ensure image clarity, avoiding duplication, and minimising motion blur. Maintaining image quality control is vital in image-based classification, as reliability is heavily influenced by frame clarity and consistency (Page et al., 2016*).* Ensuring that each of these criteria was met was necessary to achieve an accurate

spatial representation of benthic features, as the risk of misclassification increased with declining image quality, severely affecting the study's outcome.

Using ArcGIS Pro's FMV function enabled precise spatial referencing when mapping the diver's position using video-derived points; however, the workflow at times displayed limited tolerance for user error. A minor misplacement of any point during the annotation stage would require a restart, leading to inefficiencies that become significantly more pronounced in longer video sequences. Although these constraints had no impact on data quality or outcomes, they highlight a minor limitation in the scalability of FMV-based approaches when working with large reef datasets (González-Rivero et al., 2020*)*.

Ensuring that each point is both aligned and timed as accurately as possible is crucial to the success of frame extraction using the FFmpeg script. Even minor discrepancies in timestamp synchronisation could potentially disrupt spatial alignment, requiring timestamps to be consistent across the RPA and underwater datasets. While these issues were manageable by carefully reviewing each video and noting each instance of the diver submerging, this underscores the importance of synchronisation protocols when working with multiple videos for spatial analysis (Yang et al., 2025*)*.

With thousands of frames requiring individual processing, manual classification was time-intensive and could lead to analyst fatigue. Examining over 2,500 frames, each containing nine classification points, required constant attention to ensure consistency during prolonged working sessions. To mitigate this risk, processing was performed in structured intervals, maintaining consistency by referring to the pre-existing classified dataset produced by Martin (2024), and only classifying additional categories where necessary following supervisory guidance. In addition, each frame was independently reviewed by Daniel Breen to reduce confirmation bias and ensure the findings are reliable and accurate (Page et al., 2016*).*

Despite most frames remaining clear, turbidity and changing light conditions reduced visibility in some frames during classification along the reef flat. Deeper regions were difficult to distinguish at times, reducing confidence in benthic identification in some areas. Turbid reef environments are known to alter underwater light conditions and visibility, influencing image-based interpretation (Jones et al., 2021). As a result, conservative decisions were made during image-based classification to minimise misclassification risk. These conditions underscore the importance of quality control procedures when applying image-based approaches in dynamic reef-flat environments.

6 Conclusion

This thesis mapped and assessed benthic species and substrata across the northern reef flat of Vavanga Village, Kolombangara Island, Solomon Islands. This was achieved through an integrated image-based monitoring workflow combining RPA Full Motion Video, synchronised underwater imagery, manual benthic classification and spatial analyses. It addressed a significant monitoring gap in shallow fringing reef environments, particularly those influenced by strong land-sea interactions and located around under-represented Pacific Island settlements.

The results of this thesis illustrate a clear and ecologically meaningful spatial organisation of benthic communities across the Vavanga fringing reef. Hard coral was significantly concentrated along the reef crest and adjacent areas. Branching taxa such as *Acropora* and *Pocillopora,* were largely restricted to these zones of high-energy. In contrast, *Porites* corals showed a much broader distribution, with occurrences extending beyond the intermediate reef flat zones, suggesting greater tolerance to hydrodynamic variability and moderate sedimentation. Consolidated coral rock and coral rubble were more abundant at the reef crest, whereas sand, seagrass, and various macroalgae increased across the more sheltered central and inshore reef flat. Together, these findings established the Vavanga reef flat as a region that is not spatially uniform but instead structured by strong environmental gradients operating over short distances. Hydrodynamic exposure was the primary structuring force across the reef flat, whereas river influence and sediment-associated processes provided a secondary layer of environmental control.

This thesis demonstrated how a synchronised aerial and video workflow can provide a useful, easily repeatable approach for future monitoring in shallow environments. The use of the ReefCloud software demonstrated the capabilities of human-AI hybrid monitoring approaches, while also highlighting limitations. Repeated monitoring of the Vavanga reef flat would enable future surveys to detect changes in benthic assemblages, coral cover, and substrate composition over time. This includes surveys conducted following thermal stress, catchment disturbance or changes in local use and management. Future studies would strongly benefit from integrating spatial benthic mapping with environmental monitoring, including turbidity, sedimentation, hydrodynamic processes, and water quality, alongside fisheries and socio-ecological assessments. There is also significant value in expanding participatory and community-based monitoring to further support local governance, customary marine tenure, and adaptive management.

Sustained long-term monitoring of fringing reefs worldwide helps us understand temporal trends in coral cover, structural complexity and overall biodiversity (*Heenan et al., 2017)*. The importance of monitoring becomes increasingly pronounced amidst accelerating climate pressures, including rising sea surface temperatures and frequent thermal stress events. Consistent, high-resolution long-term monitoring frameworks enable the detection of early warning signs of stress on fringing reefs, including bleaching events and shifts in species composition (*Hughes & Connell, 1999).* In regions such as the Solomon Islands, where communities are heavily dependent on reef ecosystems for both subsistence and income, establishing repeatable, spatially explicit monitoring baselines is crucial to supporting both ecological resilience and informed governance.

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Appendices

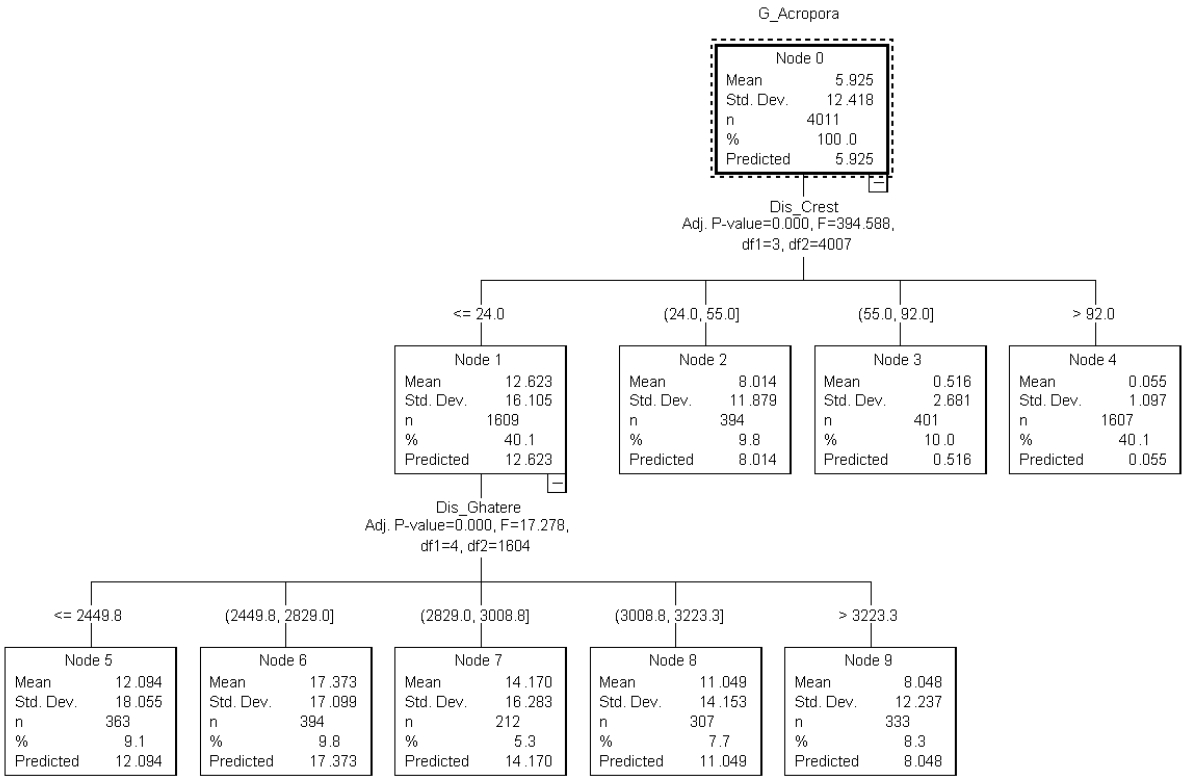
Appendix 1. Summary of underwater video transects conducted across the northern reef flat, including transect identifier, survey date, activity designation, diver, and the number of extracted video frames retained for benthic classification.

Transect ID	Date	Activity	Diver	Frames Retained
T1	6th	_2_hightide_scooty_North	Armagan	**142**
T2	6th	_2_hightide_scooty_North	Armagan	**141**
T3	6th	_2_hightide_scooty_North	Dan	**273**
T4	8th	_2_Afternoon_Scooty_after_thunder_North_A	Dan	**193**
T5	8th	_2_Afternoon_Scooty_after_thunder_North_A	Dan	**249**
T6	**9th**	_2_Scooty_AreaC_with_shark	**Dan**	**189**
T7	**9th**	_2_Scooty_AreaC_with_shark	**Dan**	**219**
T8	**11th**	_2_Scooty_Reef_front_survey_NorthSide	**Grace**	**156**
T9	**11th**	_2_Scooty_Reef_front_survey_NorthSide	**Grace**	**251**
T10	**12th**	A_5_North_Scooty_ZigZag_x3Flights_against_current	**Dan**	**83**
T11	**12th**	A_5_North_Scooty_ZigZag_x3Flights_against_current	**Dan**	**126**
T12	**12th**	A_5_North_Scooty_ZigZag_x3Flights_against_current	**Dan**	**101**
T13	**14th**	A_2_FarNorth_Scooty	**Grace**	**213**
T14	**14th**	A_2_FarNorth_Scooty	**Grace**	**211**

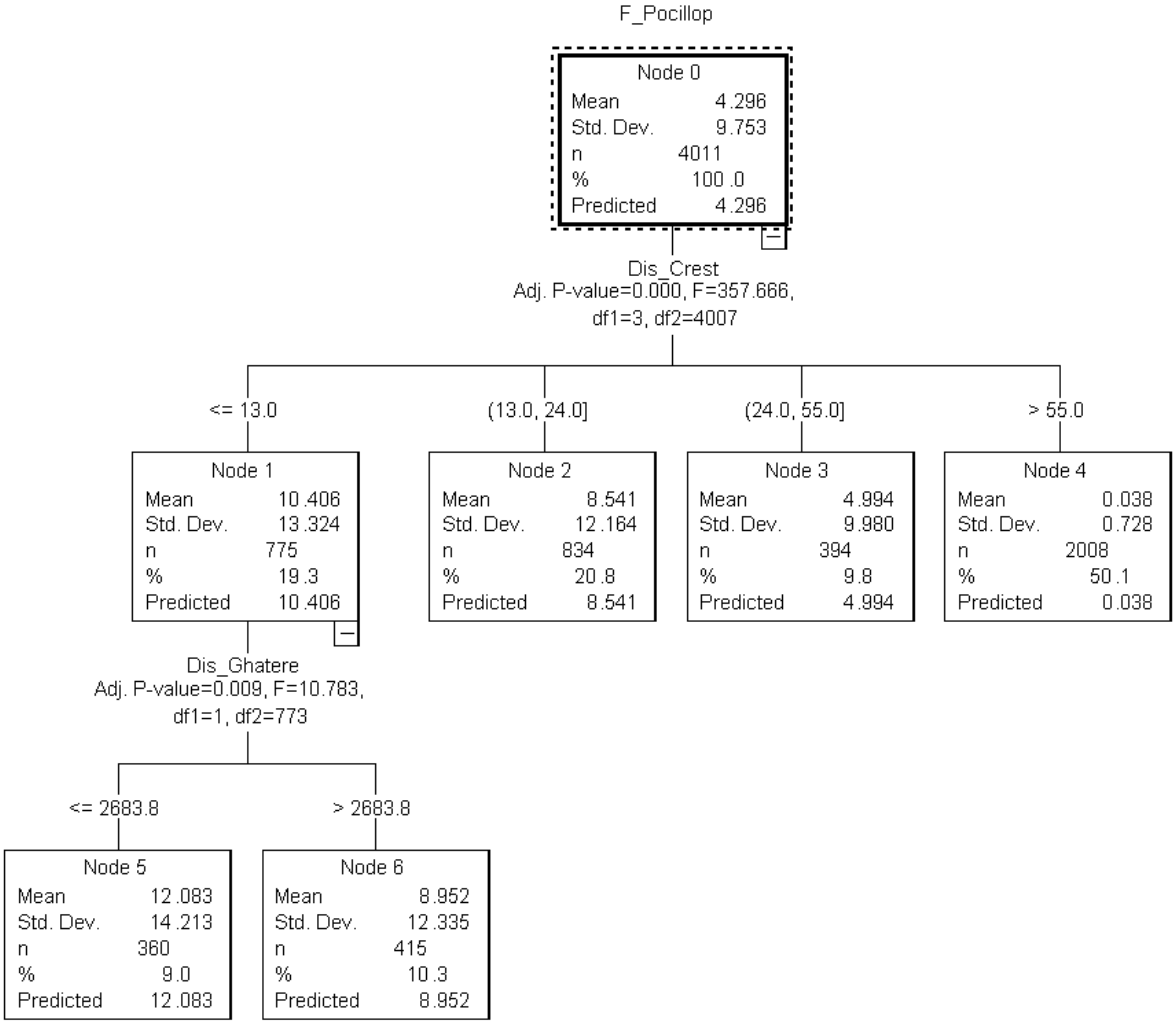
Appendix 2**.** Benthic taxa and substrate categories identified during manual image classification of reef survey frames from the Vavanga reef flats. Classification codes correspond to labels used during the manual annotation process.

Code	Taxon/Substrate	Benthic Category
Scuz	Unable to classify	Unknown
CR	Coral Rubble	Abiotic Substrate
CCR	Consolidated Coral Rock	Abiotic Substrate
Sfin	Fine Sand	Abiotic Substrate
Scor	Coarse Sand	Abiotic Substrate
SeaTha	*Thalassia hemprichii*	Seagrass
AlHal	*Halimeda spp.*	Macroalgae
AlPad	*Padina* spp.	Macroalgae
AlSarEch	*Sargassum echinocarpum*	Macroalgae
AlTurorn	*Turbinaria ornata*	Macroalgae
Pocdam	*Pocillopora damicornis*	Hard coral
Pocmea	*Pocillopora meandrina*	Hard coral
Pociver	Pocillopora verrucosa	Hard coral
Acrohumi	*Acropora humilis*	Hard coral
Acrohya	*Acropora hyacinthus*	Hard coral
Acrocor	*Acropora corymbosa*	Hard coral
Acroflor	*Acropora florida*	Hard coral
Acrodigf	*Acropora digitifera*	Hard coral
Porcyl	*Porites cylindrica*	Hard coral
Pormas	Massive *Porites*	Hard coral
Mondig	*Montipora digitata*	Hard coral
M_Foliose	*Montipora foliosa*	Hard coral
Pladae	*Platygyra daedalea*	Hard coral

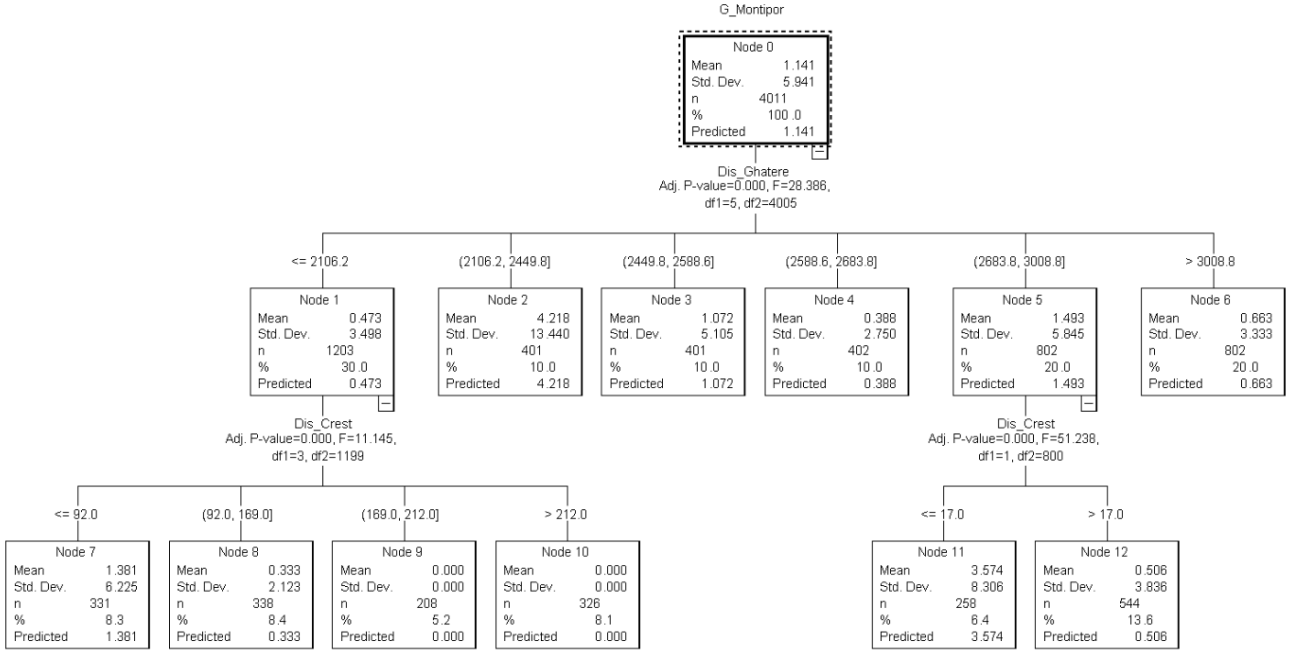
Gonret	*Goniastrea retiformis*	Hard coral
Gonedw	*Goniastrea edwardsi*	Hard coral
Faviaspp	*Favia* spp.	Hard coral
Millbra	*Millepora* branching fire coral	Hydrocoral
Spo	Sponge spp.	Invertebrate
Linkia laevigata	*Linckia laevigata*	Invertebrate



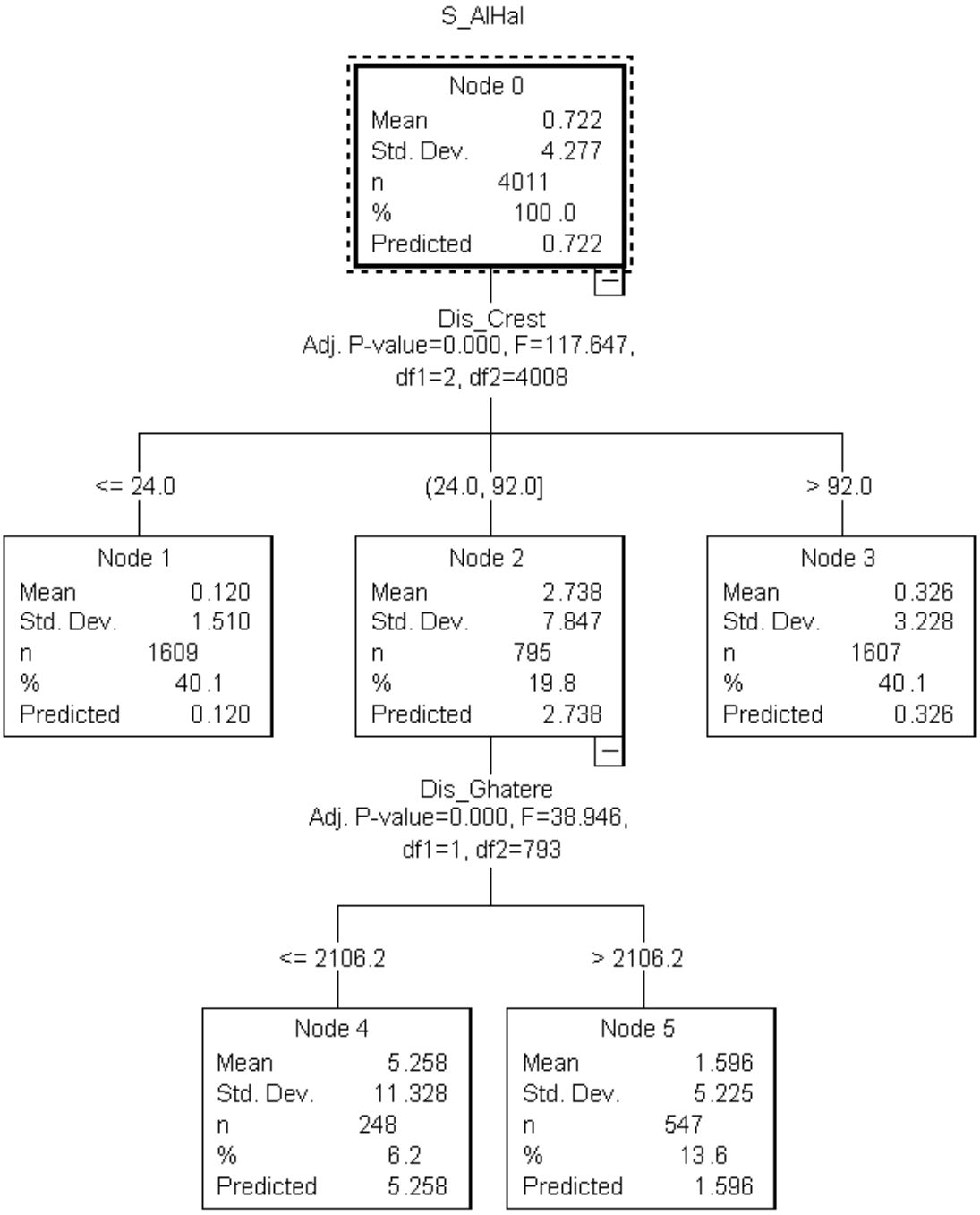
Appendix 3. Classification and regression tree (CART) model predicting the percentage cover of *Acropora* across the north reef flat. The primary split occurred along distance from the reef crest (Dis_Crest*),* with secondary subdivision by distance from the Ghatere river outlet (Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



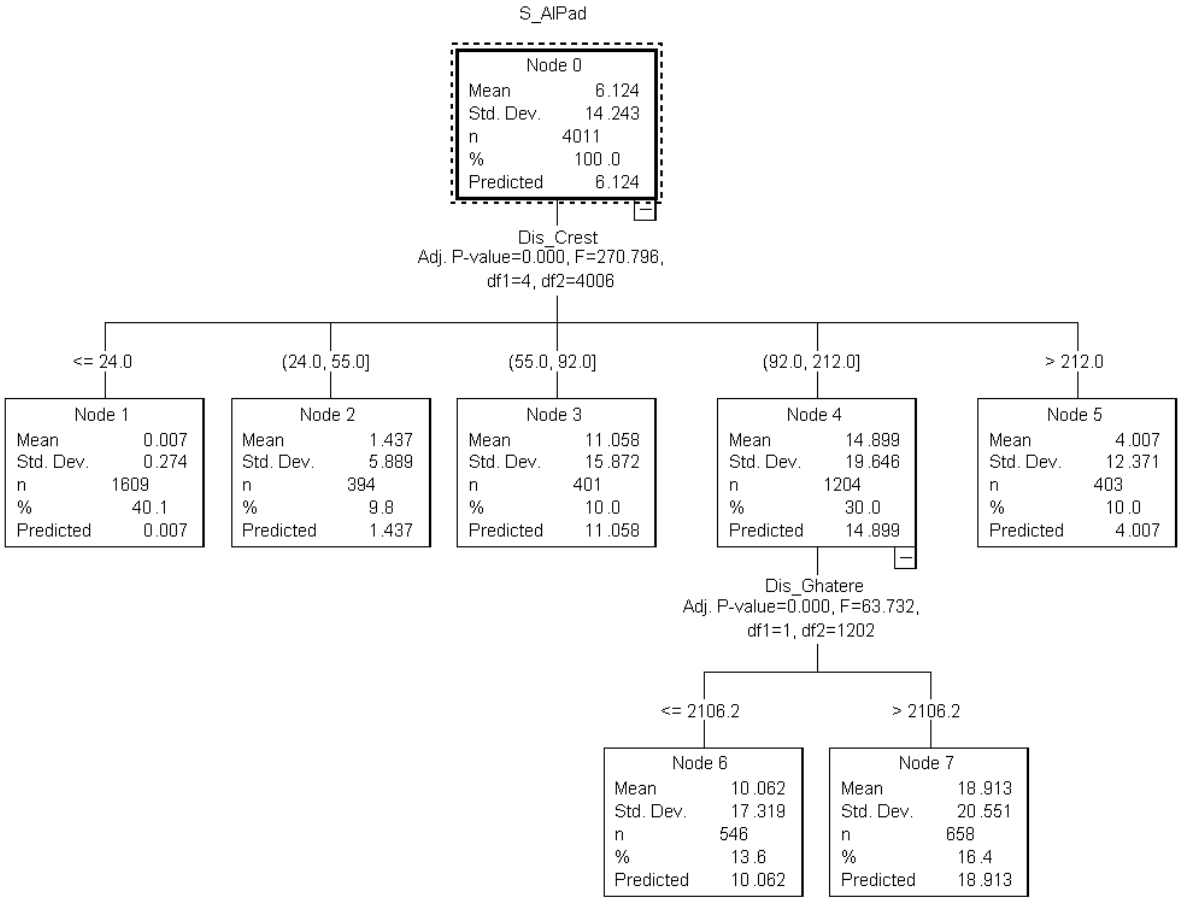
Appendix 4. Classification and regression tree (CART) model predicting the percentage cover of *Pocillopora* across the north reef flat. The primary split occurred along distance from the reef crest (Dis_Crest*),* with secondary subdivision by distance from the Ghatere river outlet (Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



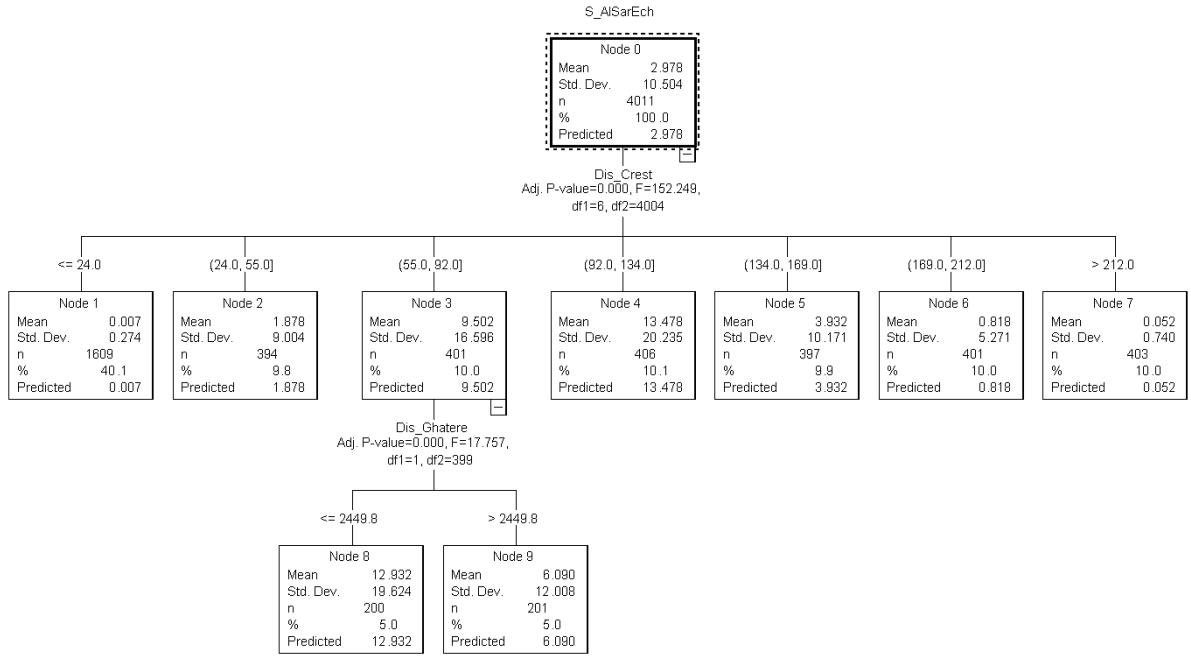
Appendix 5. Classification and regression tree (CART) model predicting the percentage cover of *Montipora* across the north reef flat. The primary split occurred along distance from the Ghatere river outlet (Dis_Ghatere*),* with secondary subdivision by distance from the reef crest (Dis_Crest). Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



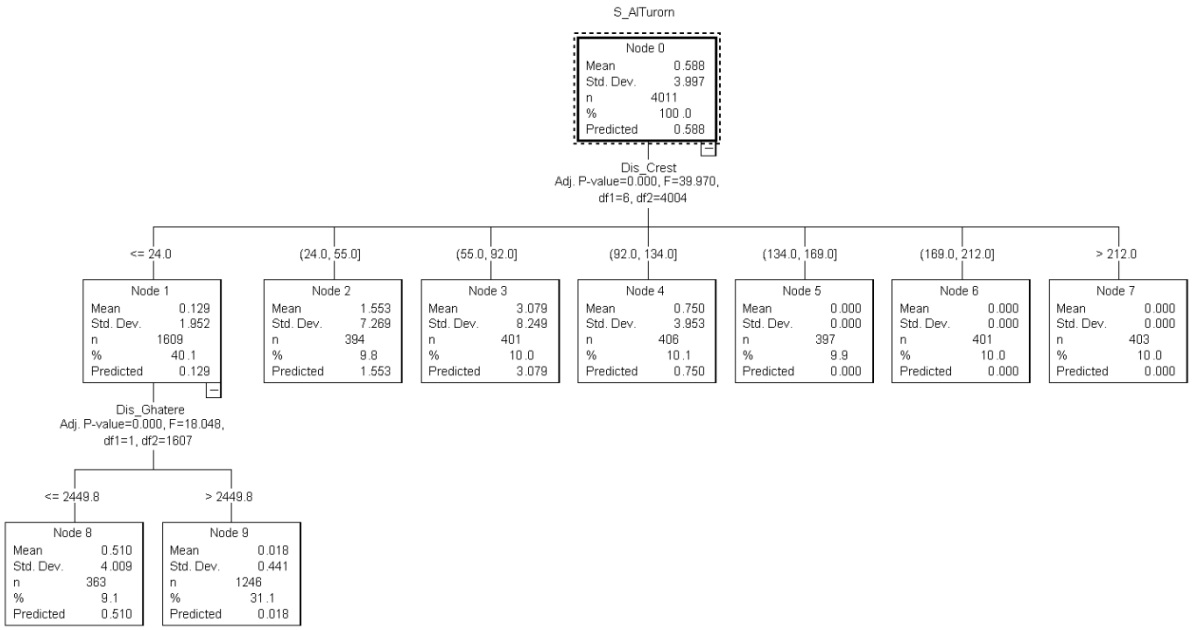
Appendix 6. Classification and regression tree (CART) model predicting the percentage cover of *Halimeda* across the north reef flat. The primary split occurred along distance from the reef crest *(*Dis_Crest*),* with secondary subdivision by distance from the Ghatere river outlet *(*Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



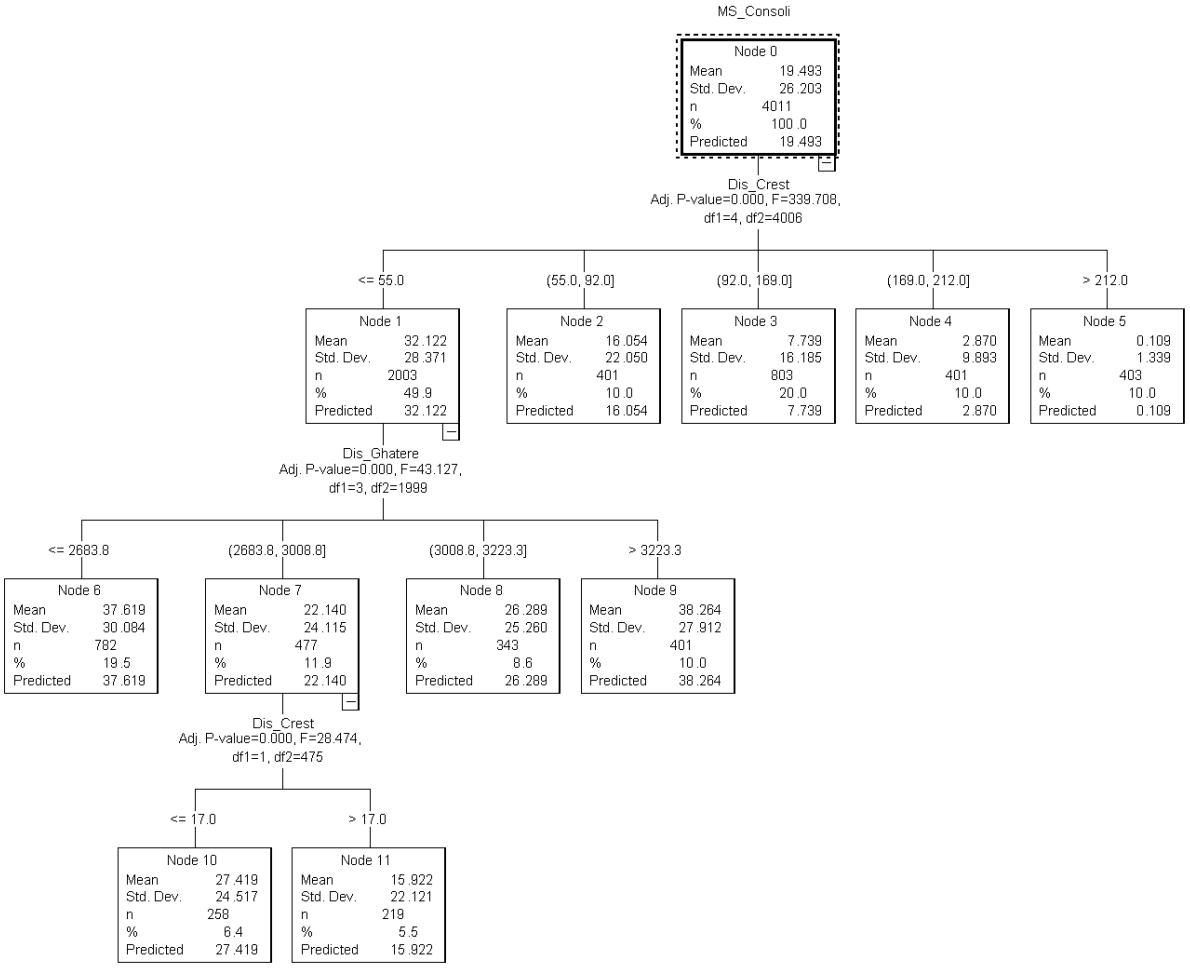
Appendix 7. Classification and regression tree (CART) model predicting the percentage cover of *Padina* across the north reef flat. The primary split occurred along distance from the reef crest (Dis_Crest), with secondary subdivision by distance from the Ghatere river *outlet (*Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



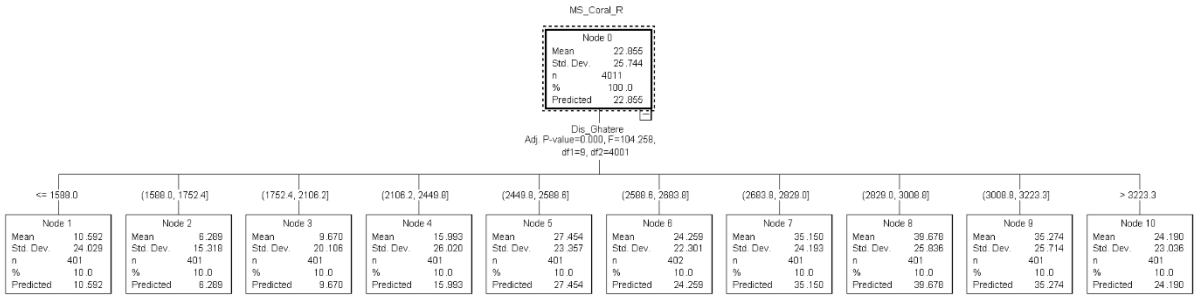
Appendix 8. Classification and regression tree (CART) model predicting the percentage cover of *Sargassum* across the north reef flat. The primary split occurred along distance from the reef crest *(*Dis_Crest*),* with secondary subdivision by distance from the Ghatere river outle*t (*Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



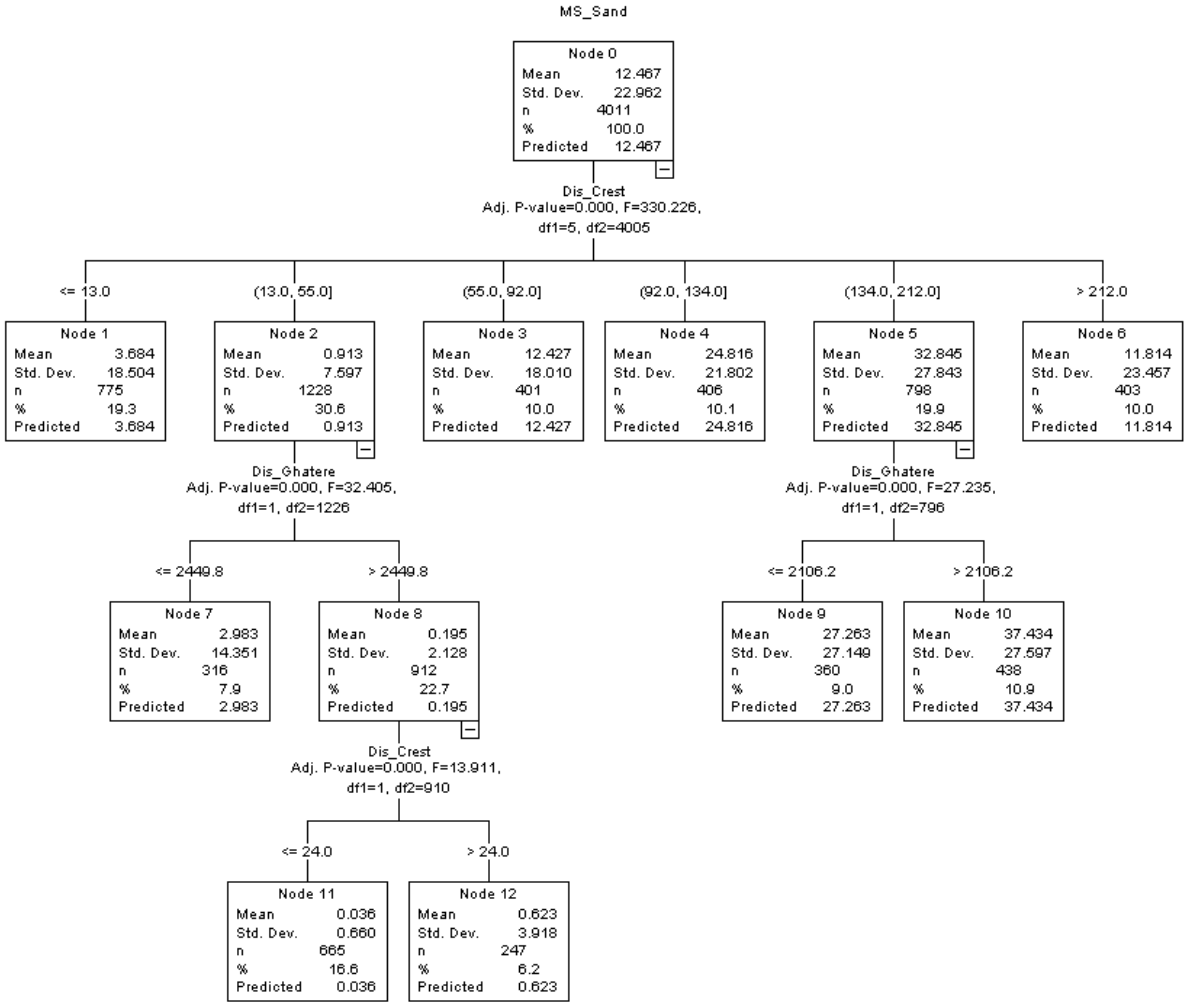
Appendix 9. Classification and regression tree (CART) model predicting the percentage cover of *Turbinaria ornata* across the north reef flat. The primary split occurred along distance from the reef crest *(*Dis_Crest), with secondary subdivision by distance from the Ghatere river outlet *(*Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



Appendix 10. Classification and regression tree (CART) model predicting the percentage cover of consolidated coral rock across the north reef flat. The primary split occurred along distance from the reef crest *(*Dis_Crest*),* with secondary subdivision by distance from the Ghatere river outlet (Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



Appendix 11. Classification and regression tree (CART) model predicting the percentage cover of coral rubble across the north reef flat. The model identified distance from the Ghatere river outlet *(*Dis_Ghatere*)* as the primary predictor. Node values display the mean predicted percentage cover, standard deviation, and sample size (n).



Appendix 14. Classification and regression tree (CART) model predicting the percentage cover of sand across the north reef flat. The primary split occurred along distance from the reef crest (Dis_Crest*),* with secondary subdivision by distance from the Ghatere river outlet (Dis_Ghatere*).* Node values display the mean predicted percentage cover, standard deviation, and sample size (n).