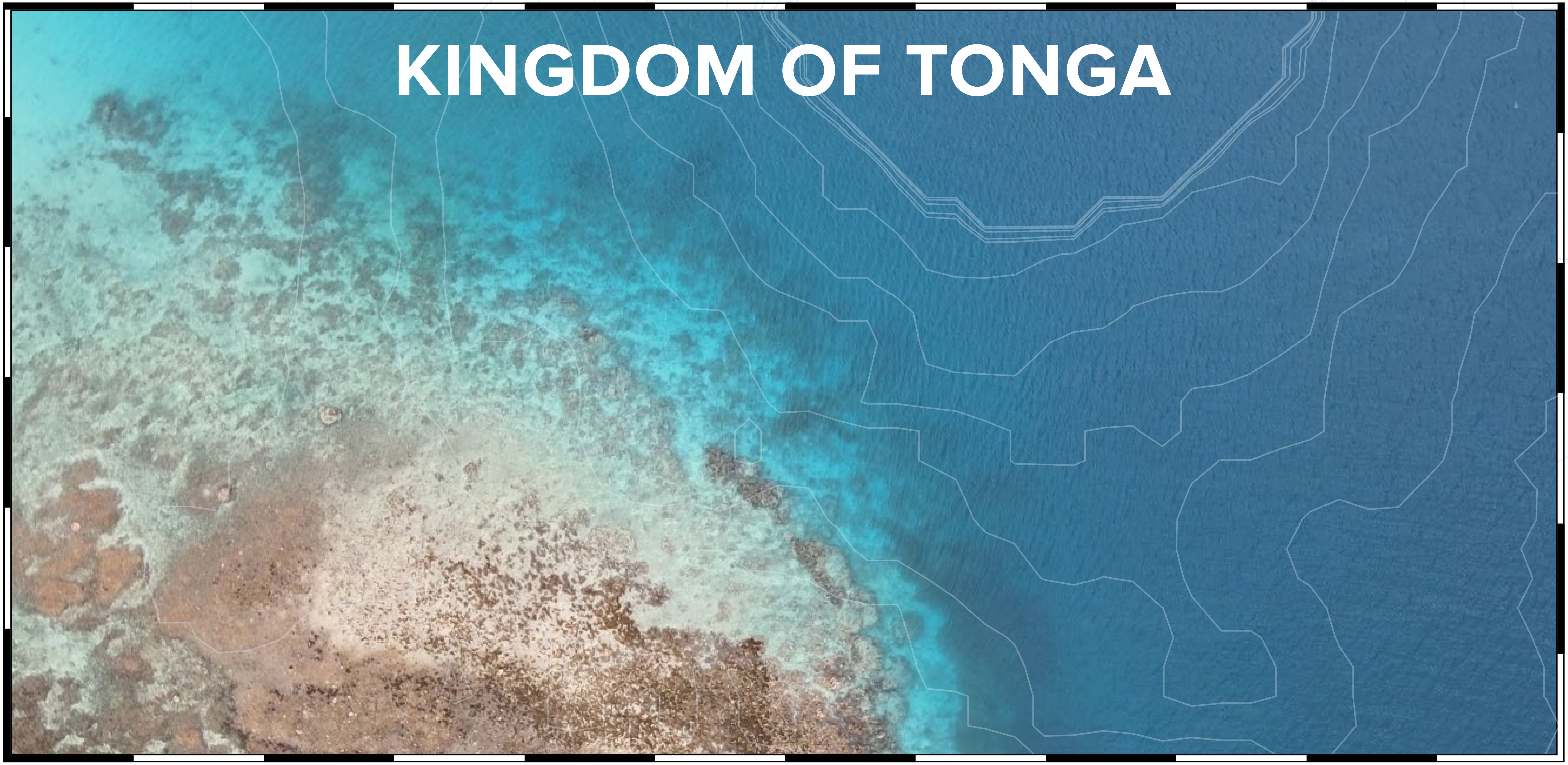
ATLAS OF COASTAL MARINE HABITAT

KINGDOM OF TONGA



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ATLAS OF COASTAL MARINE HABITAT

KINGDOM OF TONGA

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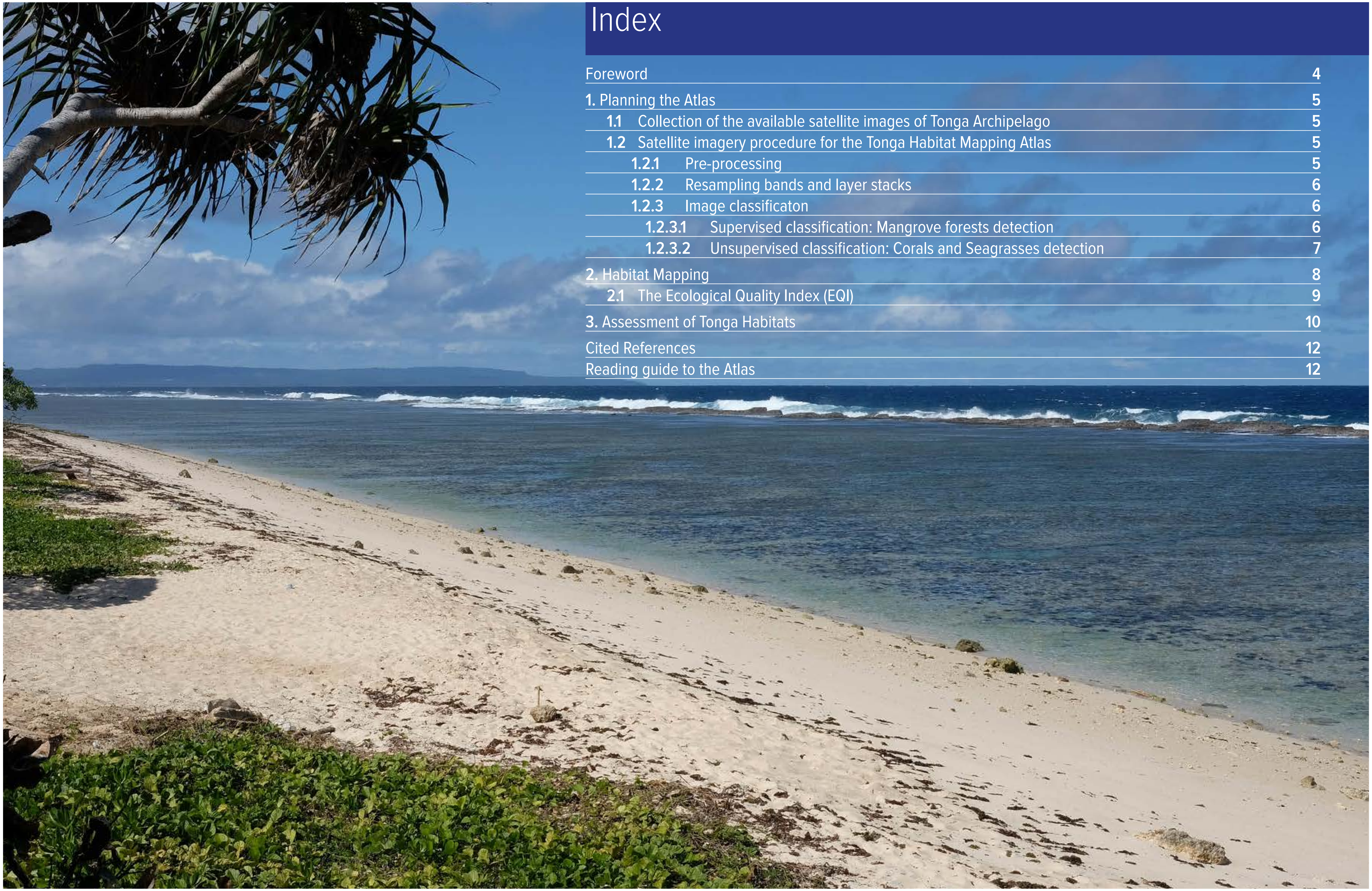

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Foreword

During the 11th Joint Committee held in July 2017 in New York in the presence of Tongan and Italian delegations at the Ocean Conference, the project "Strengthening Protected Area Management in the Kingdom of Tonga" was discussed and approved on 21 July 2017.
The project evidenced the lack of the quantitative representation of biodiversity and the absence of a biodiversity data management system to assist environmental managers in decision-making and planning. It was outlined that the Earth Observation System (EOS) and the thematic maps produced through the processing of multispectral satellite data represent the cognitive tools necessary for the habitat management of coral reef systems and associated coastal environments, such as mangroves and seagrasses. EOS contributes to document habitat status and monitor changes over time, to quantify damage and habitat vulnerability in areas of high natural and economic value and forecast future environmental changes in order to define interventions of risk factor reduction.
Based on these premises, the Work Package 3 of the project was focused on the following activity: 'Establish coral reefs systems to detect and quantify habitat changes and vulnerability of coral reefs', aimed to detect and quantify habitat changes and vulnerability of coral reefs systems and associated coastal environments through the use of habitat maps.
According to the agreement taken between Tongan and Italian delegations at the Ocean Conference in 2017, the project involves ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) as technical partner.
On 30 January 2019, the Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communications (MEIDECC) officially requested to the Italian Ministry for the Environment, Land and Sea (ISMEL) to directly finance ENEA to facilitate the upcoming activities of the project for the implementation of Work Package 3. Funding was officially approved by the Italian Government the 16 May 2019, and activities were officially financed to ENEA in October 2019.

1 Planning the Atlas

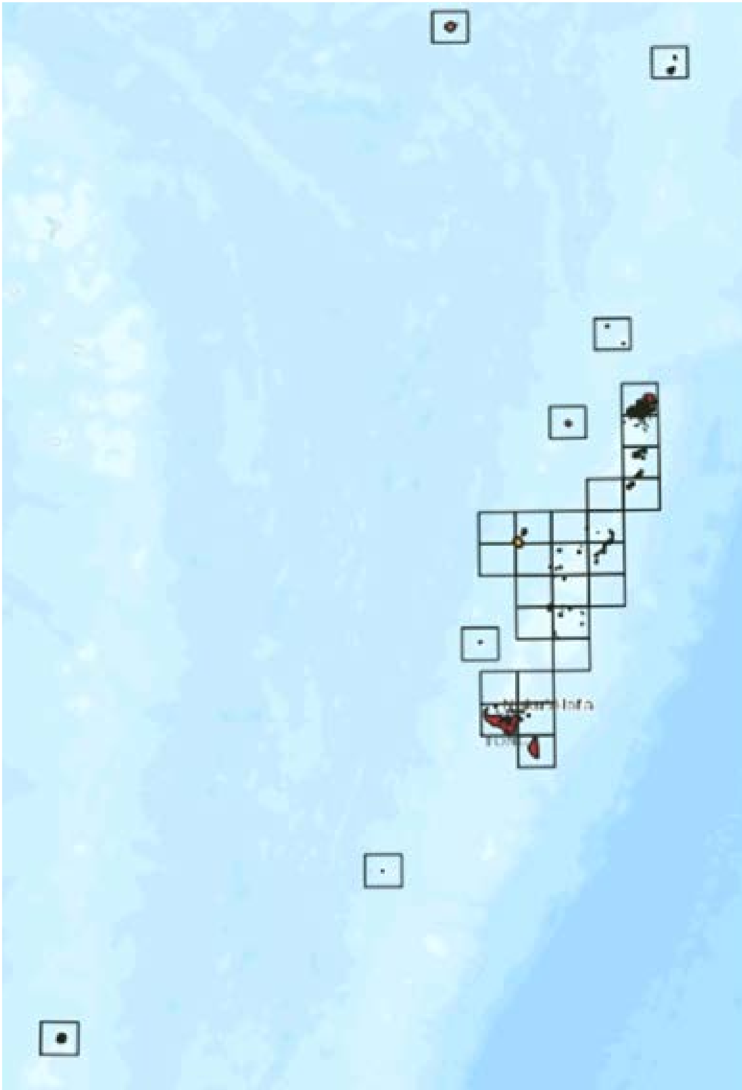


Fig. 1. The 25 tables of the Tonga's Atlas of Marine Habitats.

The planning of the Atlas on marine coastal habitats of Tonga was based on a preliminary analysis of available information on habitat mapping studies performed in Tonga Archipelago regarding corals, seagrasses and mangroves.
Based on updated knowledge gathered from dataset, maps and atlas available for Tonga Archipelago, ENEA planned the Atlas of marine habitats of Tonga with the following objectives:

- Focus on the biological communities most sensitive to climate change as corals, seagrasses and mangroves.
- Implement information on benthic habitat mapping through the analysis of the most recent satellite images available from 2018 to 2019 for the whole Tonga Archipelago. We chose this time period for two reasons: 1) it is the most recent period available with clear satellite images and 2) by doing so a starting temporal point or a zero point is defined from which to start to make habitat comparison or assessment for the entire archipelago in the future.
- Define an Ecological Quality Index for each identified habitats as a tool to help future planning of Marine Protected Areas and coastal management.

Digital maps provided by the Atlas will be open and available to Tongan stakeholders (scientists or administrative personnel), as well as the database associated to the Atlas workable through open-source QGIS software (www.qgis.org). Information stored in the Atlas could be modified, updated and implemented, for example for associated species related to each habitat record. Moreover, maps on marine and terrestrial habitats could be updated and uploaded on GIS, thus offering an efficient tool for coastal planning.

1.1 Collection of the available RS images of Tonga Archipelago

The analysis of satellite repositories available for Tonga Archipelago were examined on web portals https://earthexplorer.usgs.gov/, the https://glovis.usgs.gov/app of the U.S. Geological Survey and the https://scihub.copernicus.eu/dhus/#/home of the ESA-Copernicus organisation. More recent data available for the period from the 1 January 2018 to the 1 December 2019 showed a great number of satellite images available both for the Landsat 8 and Sentinel 2 repositories. Due to the problem that in the tropics the cloud cover is observed frequently on islands the examination was restricted to images with a cloud cover < 10 %. Sentinel-2 images were chosen for the greater resolution in comparison to Landsat 8 resolution. On Sentinel-2 images a further analysis was conducted on each available image, covering hundreds of km^2 to be sure to have the best, more recent and free of clouds view for each island/groups of islands. A total of 23 Sentinel-2 images were used for the Tonga Habitat Mapping. Although the research focused on the period 2018-2019, for some areas such as Hihifo-Tafai and Tofua-Kau only 2 images without clouds dated back to 2017 were utilised. With regard to mangroves, whose identification was very often disturbed by the presence of clouds, one images dated back to 2016 for Tongatapu and one recent 2020 image for Vavau were utilized. One Landsat image, free of clouds was utilised for Ata island.
owed to cover all the Tonga's Archipelago and to prepare the 25 tables of the Atlas (Fig. 1)

1.2 Satellite imagery procedure for the Tonga Habitat Mapping Atlas

Sentinel-2 product used in this work provides orthorectified Top-Of-Atmosphere (TOA) reflectance (Level 1-C), with sub-pixel multispectral registration. Cloud and land/water masks are included in the product. Sentinel-2 products are available to users in SENTINEL-SAFE (Standard Archive Format for Europe) format, including image data in JPEG2000 format, quality indicators, auxiliary data and metadata (https://sentinel.esa.int/web/sentinel/user- guides/SENTINEL-2-msi/data-formats). For image processing we followed the procedure presented in Immordino et al. (2019) and summarised in the Fig. 2.

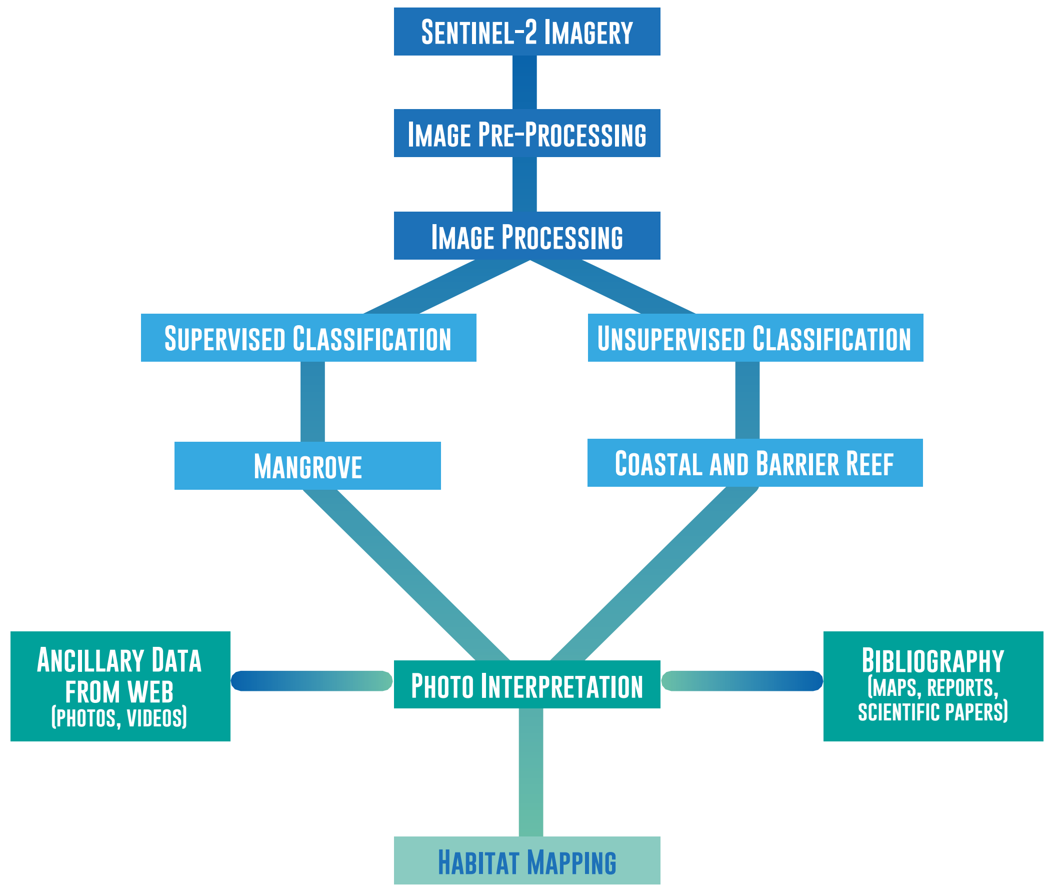


Fig. 2. Workflow diagram illustrating the steps followed for the habitat mapping (from Immordino et al.,2019, modified).

1.2.1 Pre-processing

The pre-processing steps include image radiometric, atmospheric and geometric correction (Purkis et al., 2004), sun glint correction (Kay et al., 2009; Hedley et al., 2018) application of depth invariant bands and correction for air water interface (Mumby et al., 1998; Zoffoli et al., 2014; Purkis, 2004). All of these pre-processing techniques become challenging to apply consistently at large scales. Further, there is an upper limit to what can be achieved: the mixed composition of reefs at sub-meter scales and spectral and

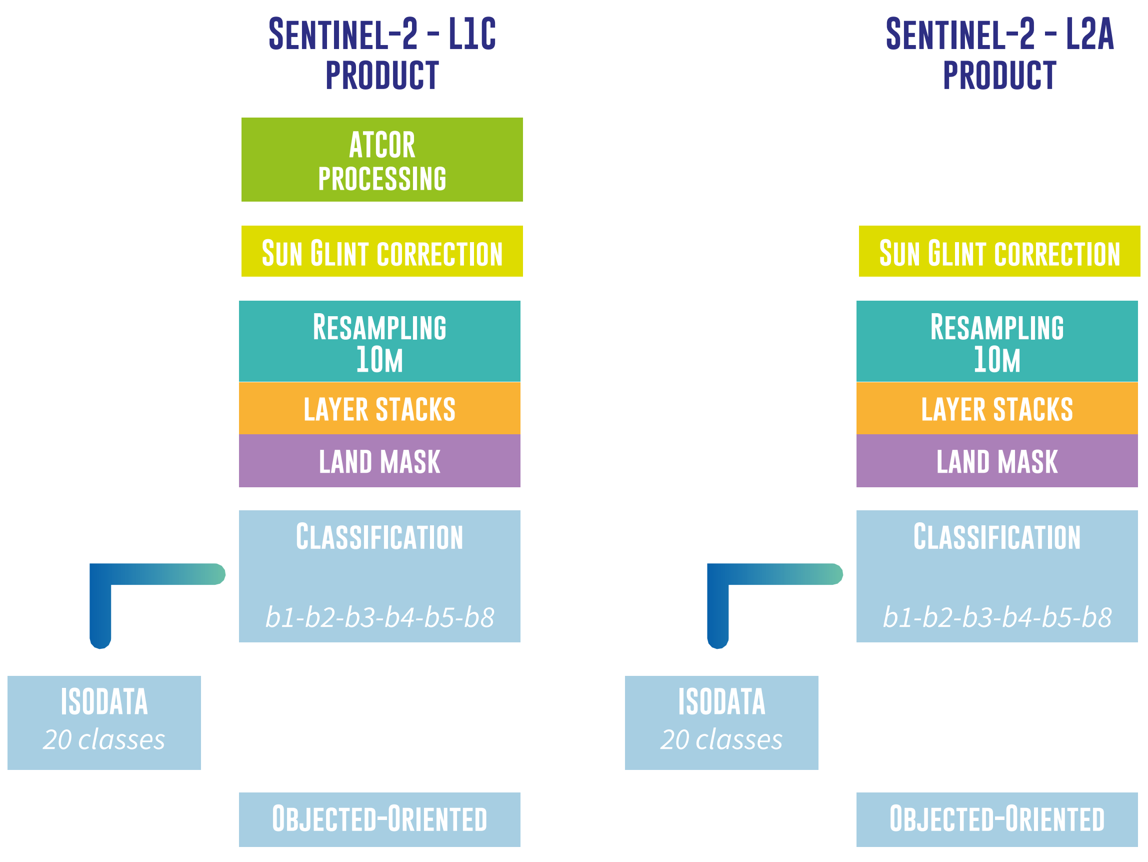


***Fig. 3.* Sentinel-2 data products: processing steps.**

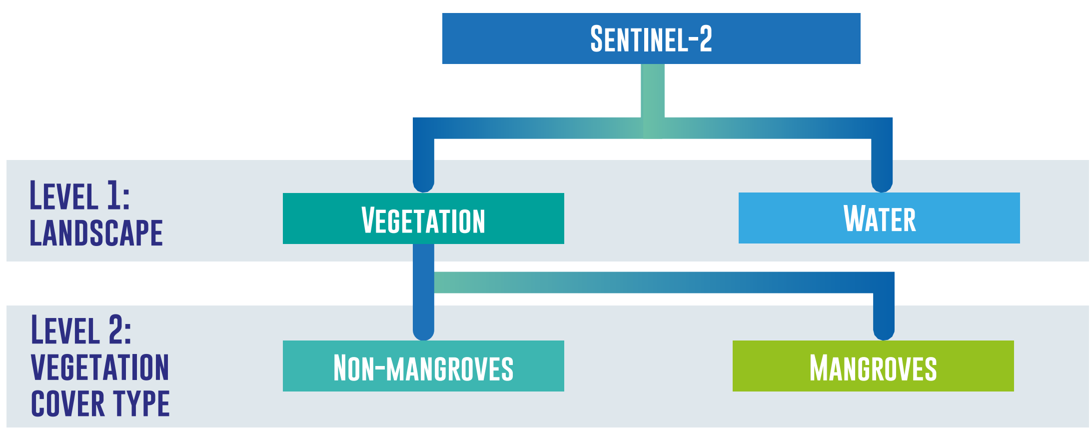


***Fig. 4.* Image object hierarchy for mangrove feature classifications (Wang et al, 2018, modified).**

structural diversity of the benthos introduces fundamental uncertainties in the relationship between benthic cover and above water reflectance. The environmental context of the reef influences the accuracy of the classification, with deeper, more turbid areas creating higher habitat mapping (from Immordino et al.,2019, modified). uncertainties for benthic mapping (Hedley et al., 2012). When using habitat maps for management activities such as marine spatial planning, these limitations can be taken into account by including explicit information on the accuracy of the features into the planning process (Tulloch et al., 2013).

1.2.2 Resampling bands and layer stacks

When an image is created through remotely sensed data, it needs to undergo some form of validation procedure using observational and/or sampling techniques; failure to do so will reduce the confidence in the final product. Nearest neighbour is a resampling method used in this work from 20m to 10m images pixel size and thus increasing to the geometric resolution of the bands. The approach assigns a value to each “corrected” pixel from the nearest “uncorrected” pixel; the advantages of nearest neighbour include simplicity and the ability to preserve original values in the unaltered scene. The re-sampled SENTINEL-2 bands were subsequently subjected to the Layer Stacking procedure obtaining a file that contained only the visible and IR bands (Fig. 3). Masks are used to exclude certain pixels from image processing or when computing image statistics; Masked pixels appear as transparent and/or dark when displayed in a view. This procedure therefore allowed to eliminate the land coverage during the classification of the marine area in the satellite image.

1.2.3 Image classification

Benthic habitats can generally be categorized according to either hierarchical geomorphological or ecological classification schemes (Mumby and Harborne, 1999; Andréfouët 2011). Digital processing includes image classification or segmentation based on spectral characteristics (i.e., digital number, radiance, or reflectance) and, in some cases, texture. Spectral processing discriminates features based solely on multispectral signatures, while texture approaches also incorporate spatial variability of the multispectral signatures. Unsupervised classification analyses images without user input, and then the different segments are assigned to a given benthic category, or class, according to expert knowledge of the user. In supervised classification, ground-truth for each class (i.e., user supplied input) is used to train the classification scheme and identify these classes throughout the image. Classification using texture considers spatial patterns as function of spectral variation within a particular area.
For all objectives to be addressed with remote sensing imagery, the environmental conditions at the moment of image capture are limiting factors: water depth, water clarity.Remote Sensing studies apply automatic *Unsupervised* and *Supervised Classifications* that allow the extraction of geo-information layers and the production of thematic maps.
Unsupervised and Supervised classification can be performed with any number of different remote-sensing or GIS-derived inputs. Commonly, spectral bands from satellite, band ratios or vegetation indices, and topographic data (e.g., elevation, slope, aspect) are used as inputs in these classifications.
Two separate approaches were used in the Atlas for the habitat mapping classification: the supervised classification was used to map littoral mangrove forests; the unsupervised classification was used to classify underwater classes related to coral platform.

1.2.3.1 Supervised classification: Mangrove forests detection

Emergent vegetation habitat composed primarily of mangrove generally found in areas sheltered from high-energy waves. This habitat type is usually found in the shoreline/intertidal or reef flat zone.
Following partially the approach applied by Wang et al. (2018), to map mangrove extent, a two-level hierarchical structure based on the spatial structure of a mangrove ecosystem and geographic object-based image analysis is utilized and modified. So, the mangrove determination in the Archipelago of Tonga was divided into two levels, namely landscape and vegetation cover type (Fig. 4).
The object-based image analysis approach was used to implement the hierarchy of Level 1 and 2. For this purpose Trimble eCognition® software was used. Creating an object-based classification mainly consists of two steps: Image segmentation and object classification. Table 2 shows the algorithm (rule set) and classification processes developed for the archipelago of the Kingdom of Tonga, in which some spectral indices are selected and combined.

***Tab. 1.* Mangrove feature classifications based on Sentinel-2 imagery (Wang et al. 2018, mod). Seg is an abbreviation for segmentation.**

Level		Sentinel-2 image (13 bands)
Level 1	Water	Chessboard Seg: 1 MNDWI > 0 FDI < 0 Brightness < 1250
	Vegetation	WFI > 0.7
Level 2	Mangroves	Multiresolution Seg: 64 300 < Band 11 (SWIR1) < 660
	Non-mangroves	Not “mangroves”

In Tab. 1, MNDWI represents the Modified Normalized Difference Water Index:

1) MNDWI = (Band 3 – Band 11)/(Band 3 + Band 11) = (Green – SWIR1)/(Green + SWIR1)

FDI represents the Forest Discrimination Index:
2) FDI = Band 8 – (Band 4 + Band 3) = NIR – (Red +Green)

and WFI represents the Wetland Forest Index
3) WFI = (Band 8 – Band 4)/Band 12 = (NIR – Red)/SWIR2

The first level was used to discriminate vegetation and non-vegetation and produced a mask of vegetation. A chessboard segmentation with an object size of one pixel was applied in order to preserve the pixel value of coarse or moderate resolution images. Following segmentation, the objects with the Modified Normalized Difference Water Index MNDWI (1) higher than zero and the Forest Discrimination Index FDI (2) less than zero were classified as water. Moreover, due to some of mudflat overlapping with water and the brightness of the mudflat being greater than water, the brightness was used as supplement to exclude these mudflats (Brightness < 1250). The second level was used to separate mangrove from non-mangrove within the vegetation mask, and Wang et al., (2018) applied the Mangrove Discrimination Index 2 (MDI2) index:

MDI2 = (Band 8 – Band 12)/Band 12 = (NIR – SWIR2)/SWIR2

Developing an efficient algorithm for mapping mangroves requires an understanding of the spectral, physical, and spatial distribution characteristic of the mangroves. There is no universal rule-set for different imagery and sites.
By applying the MDI2 index in the few islands of the Tonga archipelago where the presence of mangroves is confirmed by the bibliography, it has been observed that in this context, the use of the MDI2 index overestimates the extension of the mangroves. For this reason, it was preferred to apply a selection of the values of Band 11 (SWIR1). In particular, the definition of the spectral value range of Band 11 (SWIR1, tab. 2, level 2) must be calibrated for each Sentinel-2 image.

1.2.3.2 Unsupervised classification: Corals and Seagrasses detection

3 For the habitat classification related to coral platforms the ENVI® software was used. The ENVI algorithm showed better results with the unsupervised isodata classification performed for a maximum of 35 classes on Sentinel-2 using bands 1-2-3-4-5-8 with 10 m of resolution.
Unsupervised classification yields an output image in which a number of classes are identified and each pixel is assigned to a class (Richards, 2006). This classification often results in too many land cover classes, particularly for heterogeneous land cover types, and classes often need to be combined to create a meaningful map; the classification is useful when there is no pre-existing field data or detailed aerial photographs for the image area, and the user cannot accurately specify training areas of known cover type. In marine habitat classification, the unsupervised isodata classification is considered the most appropriate approach not supported by sea-truth validation (Mumby, 2000; Bouvet et al., 2003).
The spectral signatures of the reef cover were extracted from Sentinel-2 image as reported in Immordino et al. (2019) to show the spectral *separability among them (Fig. 5). To check the reliability of atmospheric co*rrections and subsequent classification of the Sentinel-2 image, the ROI of the coverage classes present in the coral environment was extracted.
Immordino et al. (2019) showed as the image interpretation procedure for habitat classification was based on two main components: the geomorphologic description of the seabed and the biological relevance of the associations living in the zone. According to this approach, we considered the geomorphologic description of the seabed and the biological relevance of the associations living in the two main zones of the coral reefs: the Barrier Reef and the Coastal Reef (Tab. 2).

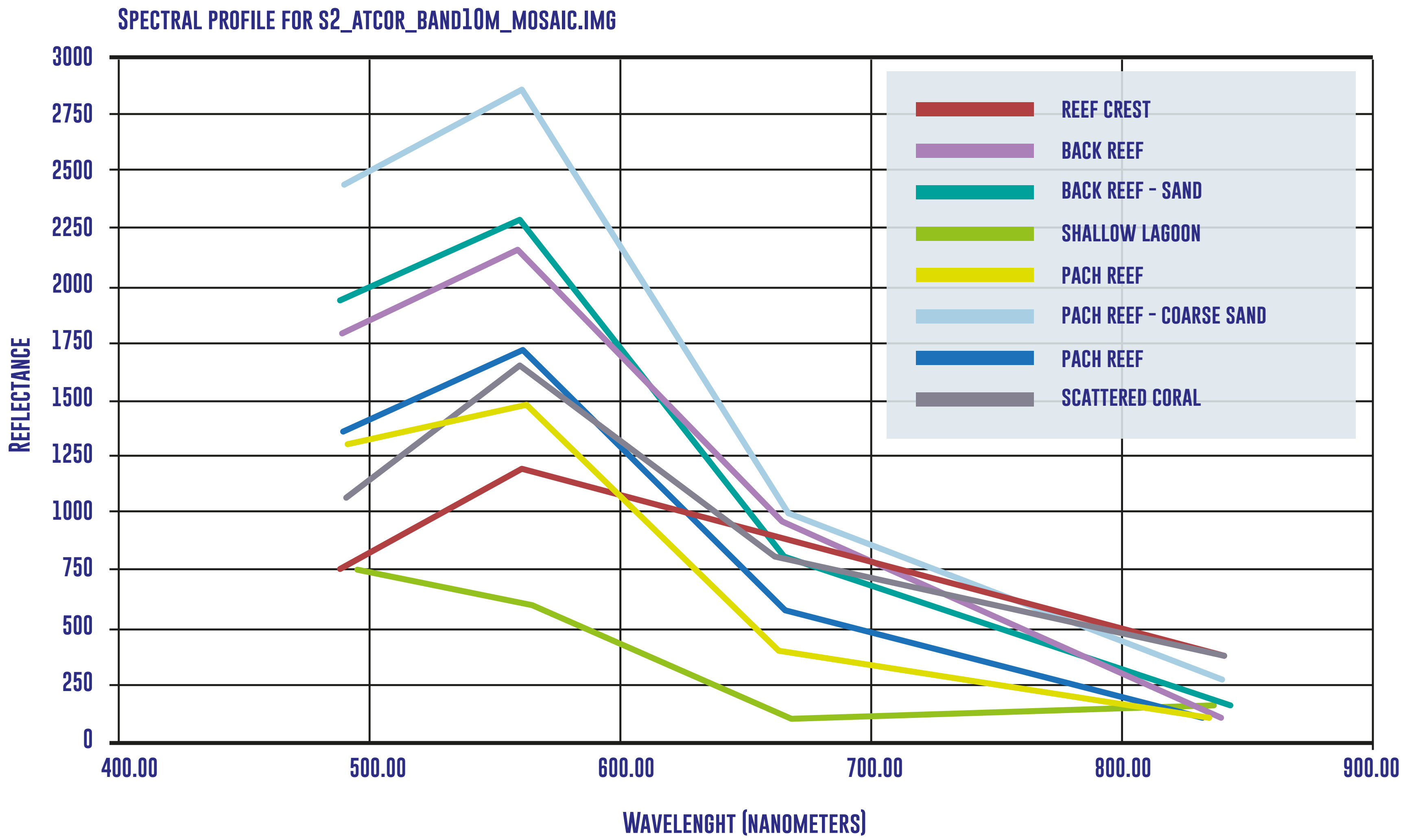
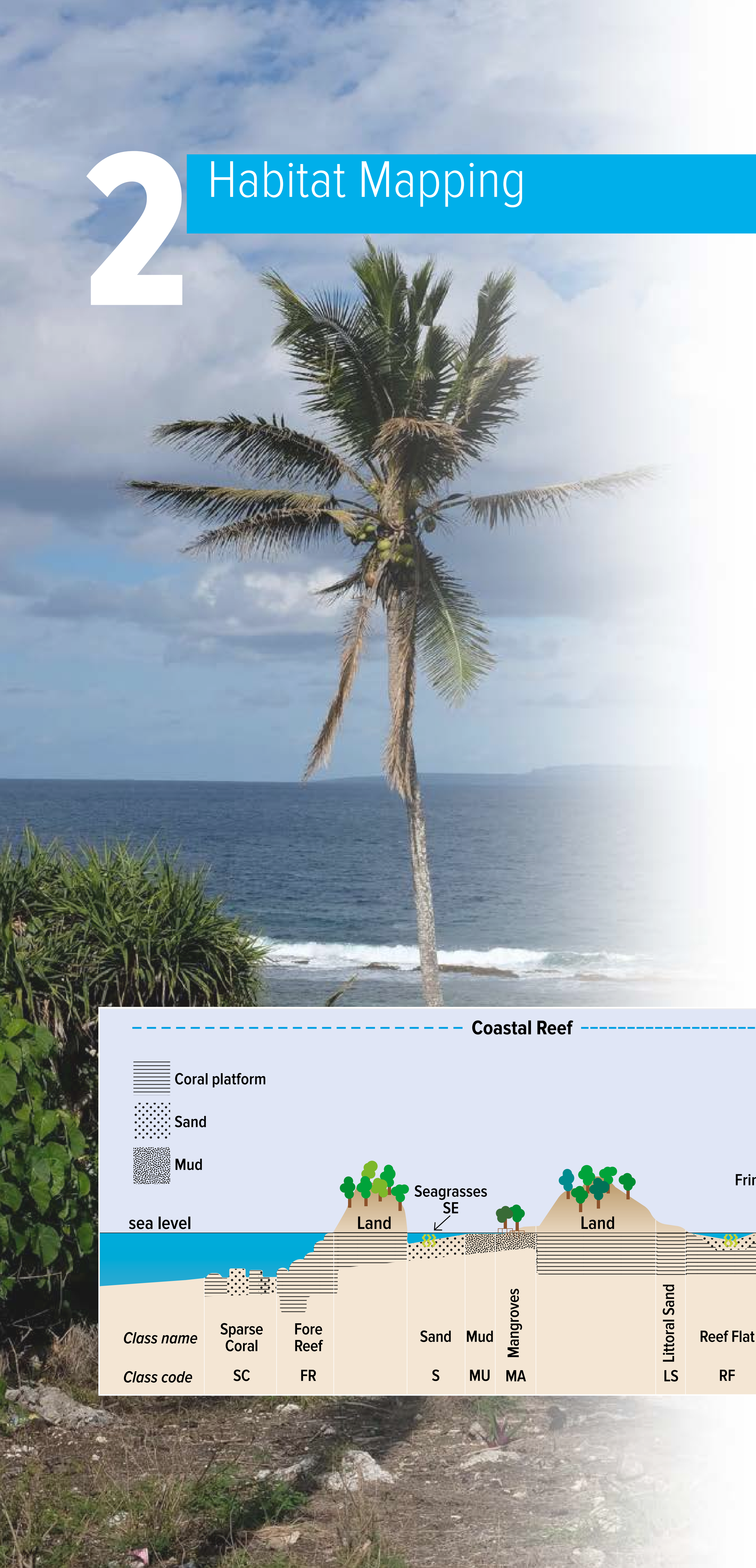


Fig. 5. Spectral signature of reef coverage (Barrier Reef zone, site 1) in Erdas software (from Immordino et al, 2019, modified).

Tab. 2. Geomorphological description and biological relevance of the main classes/subclasses used for the Palau habitat mapping with Sentinel-2 imagery (from Immordino et al., 2019, modified).

Zone	Habitat Classes	Habitat Subclasses	Geomorphological Description	Biological Relevance
Barrier Reef	Bank/shelf and Forereef	coral, coralline algae	underwater coral cliff	dense coral, high biodiversity, coral reservoir
	Reef crest	coral, coralline algae	windward coral platform shelf edge, algae ridge	dense coral, high biodiversity
	Back reef	scattered coral, flesh algae	coral platform, and channels	medium to scarce coral density
	Patch reef	coral/coralline algae	coral knob, aggregate coral	medium coral density, coral reservoir
	Lagoon	sand coral knoll, massive coral	sand, rubbles, coral	medium to dense coral density, coral reservoir
Coastal Reef	Reef crest	coral, coralline algae	seaward coastal coral platform, shelf edge	high coral density, high biodiversity, coral reservoir
	Reef flat	coral, flesh algae, seagrasses	coral platform	high coral density, high biodiversity, coral reservoir
	Uncolonized	outward limit of mangrove area	sand/ mud	nursery area for fish, shrimps, etc.
	Emergent vegetation	mangrove	intertidal/sand/mud	high primary productivity area



2 Habitat Mapping

Ancillary information such as scientific reports, literature, web-free imagery, video and photo were used for interpretation and to achieve maps of relevant habitats without field data validation.

The coastal benthic classification was based on two main components: the geomorphologic characteristics of the zone and the biological associations living in the zone. Benthic classification has been adapted to the objectives of the Atlas; in particular we gave more emphasis to biological habitats that refer to corals, seagrasses and mangroves. With the aim to identify priority habitats useful for further analysis on the environment health status, we referred mainly to NOAA Shallow-Water Benthic Habitats Manual (NOAA, 2005) and to the Millenium project (Andréfouët et al., 2005).The submerged habitats of corals and seagrasses were identified taking into consideration the actual depth limit of the satellite images, normally within 20-30 m depth, and the actual spectral and resolution limit of the Sentinel-2 satellites. Deeper areas, for example the deep lagoons or the offshore zones of Forereef (FR) and around Reef Bank (RB) should be investigated with other methodologies (transects, Multibeam, Side Scan Sonar). These deep areas are of relevant ecological importance as species of coral inhabiting these zones could be an important reservoir of larvae for the shallower reefs impacted by climate changes. In the two main morphological zones of the reef islands, the barrier reef and the coastal reef, 15 main biological habitat classes and subclasse were identified and illustrated in Fig. 7 and Tab. 3. Further 4 classes, with scarce biological relevance, were identified during habitat classification and reported in the Atlas: Sand (S), Littoral Sand or beaches (LS), Beach Rocks (BRK) and No Reefs (NR). We decided to maintain these classes for their relationships with biological ones and/or for their natural value for the Marine Protected Areas. For example, sand cover (S) may vary in season and year, seagrasses may colonise new sand bars or disappear under them. The Littoral Sand (LS) and Beach Rocks (BRK) are of relevant interest from a geomorphological and touristic point of view. The last class, the No Reef class (NR) has none biological relevance and is associated with rocky, basaltic reefs of volcanic island and/or to boulder beaches.

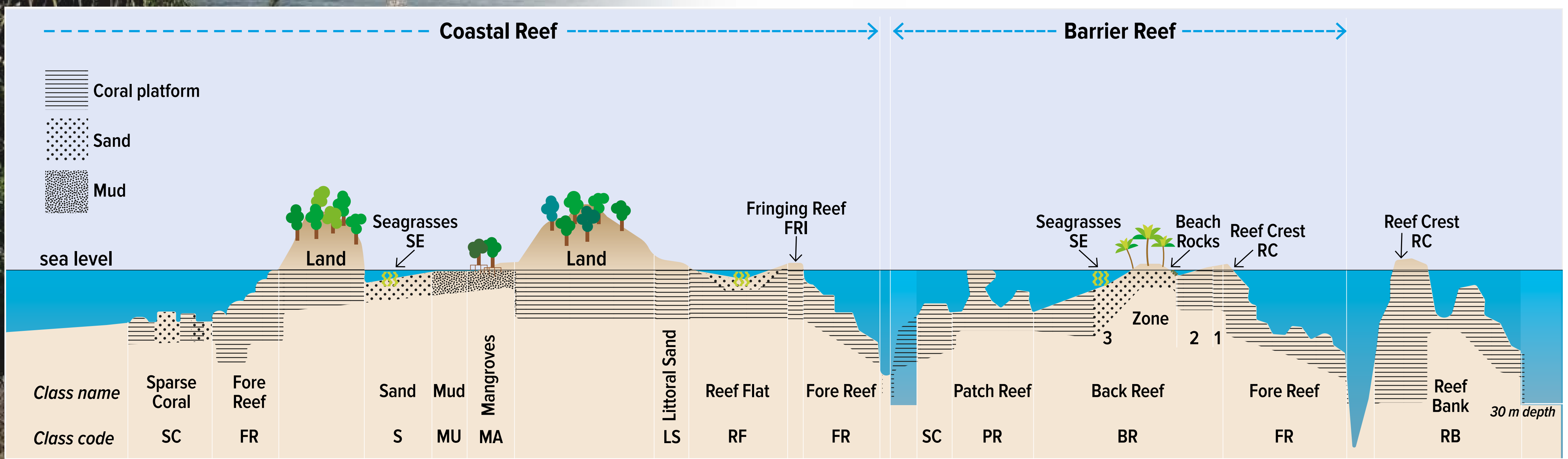


Fig. 7. Zonation of the marine shallow-water habitat classes identified and included in the Atlas of Tonga Archipelago

2.1 The Ecological Quality Index (EQI)

Defining an Ecological Quality Index associated with the presence of the habitats is a fundamental tool to help scientists and stakeholders planning Marine Protected Areas and managing coastal areas (Peirano et al., 2023).

For this reason, an Ecological Quality Index (EQI) based on the ecological relevance of each of the fifteen habitat of biological importance has been elaborated. Given the limited resolution of the satellite images (20m) and the consequent representation scale limited to 1: 50.000, the EQI was evaluated as the mean of a 3-level score/colors of ecological importance (1 = low value = green ; 2= medium value = yellow; 3 = high value = red) assigned to the six following parameters: nursery ground, connectivity, species reservoir, fish attraction, biodiversity, primary production (Tab. 3).

The EQI was integrated in the database associated to the QGIS software giving the possibility to identify on the maps the area of interest, associated habitat (Tab. 3) and quantify their ecological relevance.

Tab. 3. Main Classes/Subclasses used for the Tonga habitat mapping. Habitat Classes, with their code, and sub-zones used for shallow-water benthic habitat of Tonga islands. The Ecological Quality Index (EQI) was calculated as the mean of the scores of six ecological parameters (nursery ground, connectivity, species reservoir, fish attraction, biodiversity, primary production).

BIOLOGICAL HABITAT CLASSES	ABBREVIATION	SUB ZONES	GEOMORPHOLOGICAL SETTING	Biological value (1= low , 2 = Medium , 3 = High)						ECOLOGICAL QUALITY INDEX (EQI)
				NURSERY GROUND	CONNECTIVITY	SPECIES RESERVOIR	FISH ATTRACTION	BIODIVERSITY	PRIMARY PRODUCTION	
SPARSE CORAL	CS		Sparse colonies on sand and gravel bottoms	1	2	2	2	2	0	2
REEF BANK	RB		Offshore sparse banks and shoals in the open ocean	3	3	3	3	3	0	3
PATCH REEF	PR		Coral Pinnacles and broken reef, may reach the surface with a reef crest (RC)	2	3	3	3	3	0	3
FORE REEF	FR		Coral cliffs and continuous, dense coral beds and bank shelves outward fringing reef and barrier reef. It include spur and grooves	2	3	3	3	3	0	3
REEF CREST	RC		Outward edge of barrier reef, coral and coralline algae exposed to wave actionto and air at low tide	2	3	3	3	3	3	3
BACK REEF	BR	1	Coral and coralline algae. Just behind reef crest.	2	3	3	3	3	3	3
		2	Scattered corals and flesh algae on coral platform behind the BR zone 1	1	1	1	1	1	1	1
		1	Scattered coral on coral platform with moderate slope with sand and gravel. Between the BR zone 2 and internal lagoon and sand bar.	1	1	2	1	1	0	2
FRINGING REEF	FRI		Coral on the edge of RF. Exposed to air at low tide and to wave action.	2	2	2	3	3	1	2
REEF FLAT	RF		Coral platform among the FRI and the coast rare, sparse coral, sand patches, and algae	1	1	1	1	1	1	1
SEAGRASSES	SE	1= High Density	dense plant cover on sand patches on barrier reef in lagoons and on RF	3	3	3	3	3	3	3
		2=Low density	plant patches variable in space and time on sand bars in lagoons and on RF	2	2	1	2	2	2	2
ALGAE	AL		large patches of algae may be present on sandy and rocky bottoms of the Barrier Reef and Coastal Reef	1	1	1	2	1	3	2
MANGROVE	MA		Terrestrial plant forest implanted along coastline where rivers are present	3	3	3	3	3	3	3
MUD	MU		Mud fringe in front of mangrove water limit	2	1	1	1	0	0	1
SAND	S		Sand bottoms, sand bars	0	0	0	0	0	0	0
LITORAL SAND	LS		Beaches	0	0	0	0	0	0	0
NO REEF	NR		Rocky, basaltic reefs of volcanic island, boulder beaches	0	0	0	0	0	0	0
BEACH ROCKS	BRK		Cemented sandstone in the upper part of a beach, generally between mean sea level and mean high water levels	0	0	0	0	0	0	0

3 Assessment of Tonga Habitats

The comparison of the occurrence of the habitats of biological importance among the five Tonga Admistrative Regions, Ata Island and Minerva Reef, showed that Forereef (FR), Fringing Reef (FRI) and Reef Flat (RF) habitats were found in all the Regions with the highest cover percentages (Fig. 8). Sparse coral (SC) habitat were found in Vavau, Ha'apai and Tongatapu on littoral, sandy bottoms. Back Reef (BR) was recognized in all regions with the exception of Eua. Mangroves (MA) and the associated Mud (MU) habitat were limited to Vavau and Tongatapu, the regions with greatest islands. Seagrasses (SE) were found in all the regions with cover reaching the highest values in Tongatapu. Reef Banks (RB) were found only in Vavau and Ha'apai regions.

The comparison of the Ecological Quality Index showed that all regions have highest ecological values, from 45 % upward (Fig. 9).

The assessment of habitat of biological importance for all the Tonga archipelago showed like Forereef, Sparse Corals and Reef Banks are the habitats with the highest bottom cover respectively of 14.717 ha (FR), 14.585 (SC), and 10.791 (RB), contributing to the total highest values of EQI of 71.42 % (Fig. 11).

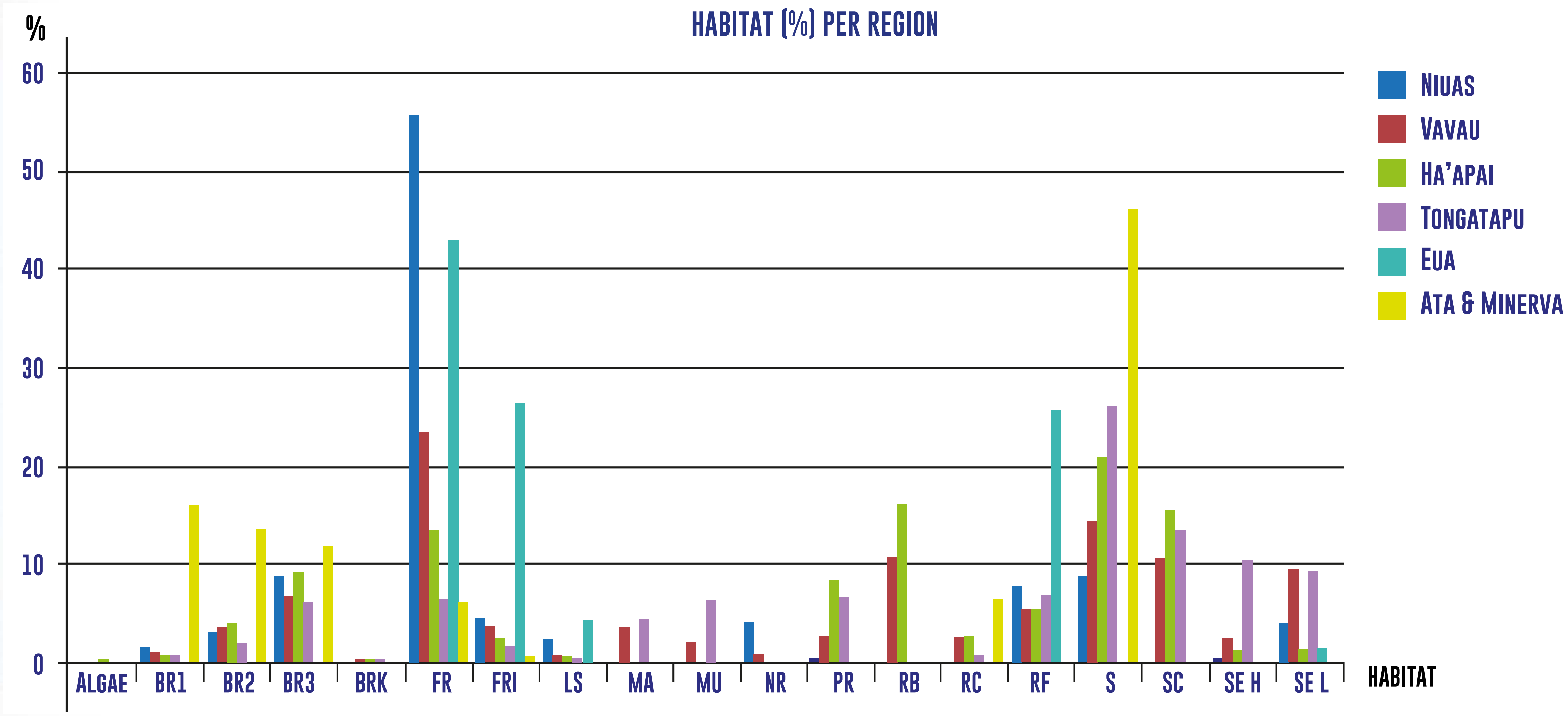


Fig. 8. Percentage occurrence of the habitats of biological importance in Tonga.

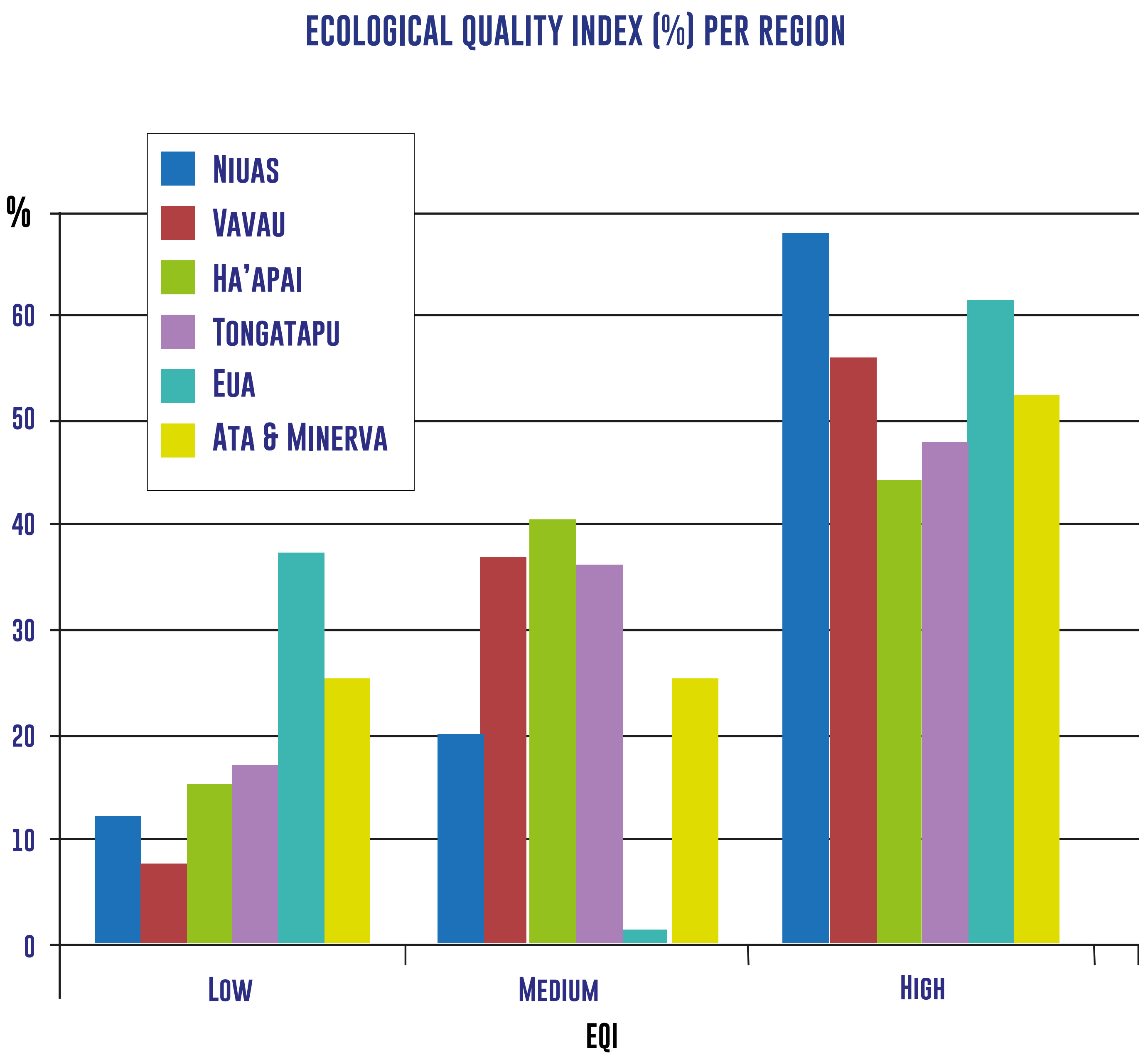


Fig. 9. EQI percentage comparison among the five administrative region in Tonga, Ata and Minerva.

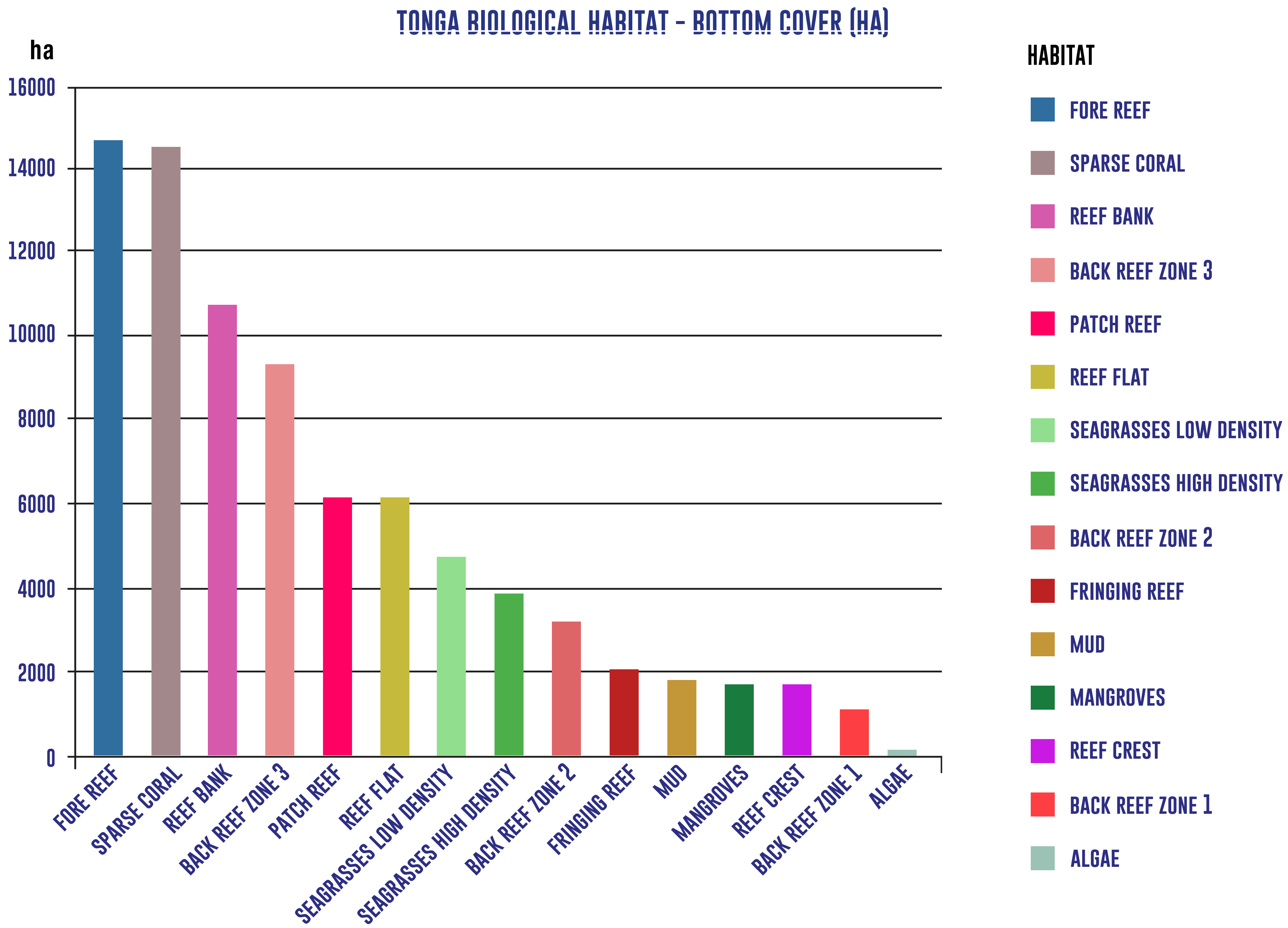


Fig. 10. Bottom cover in hectares of the 15 main biological habitat in Tonga.

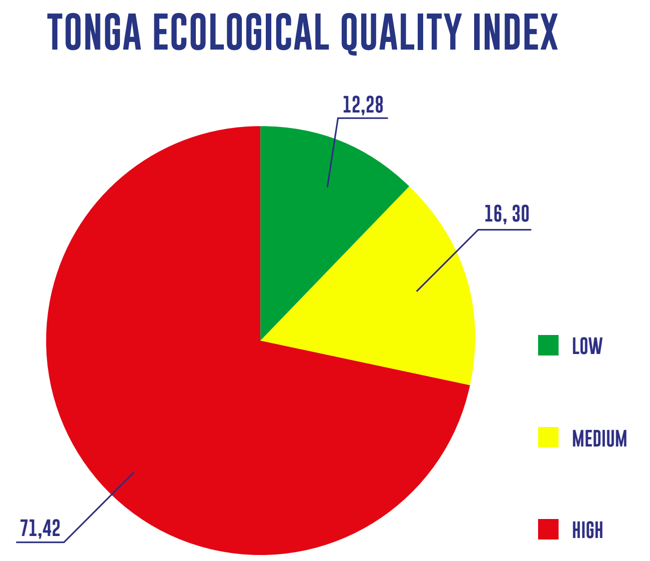


Fig. 11. Total Ecological Quality Index for Tonga Archipelago.

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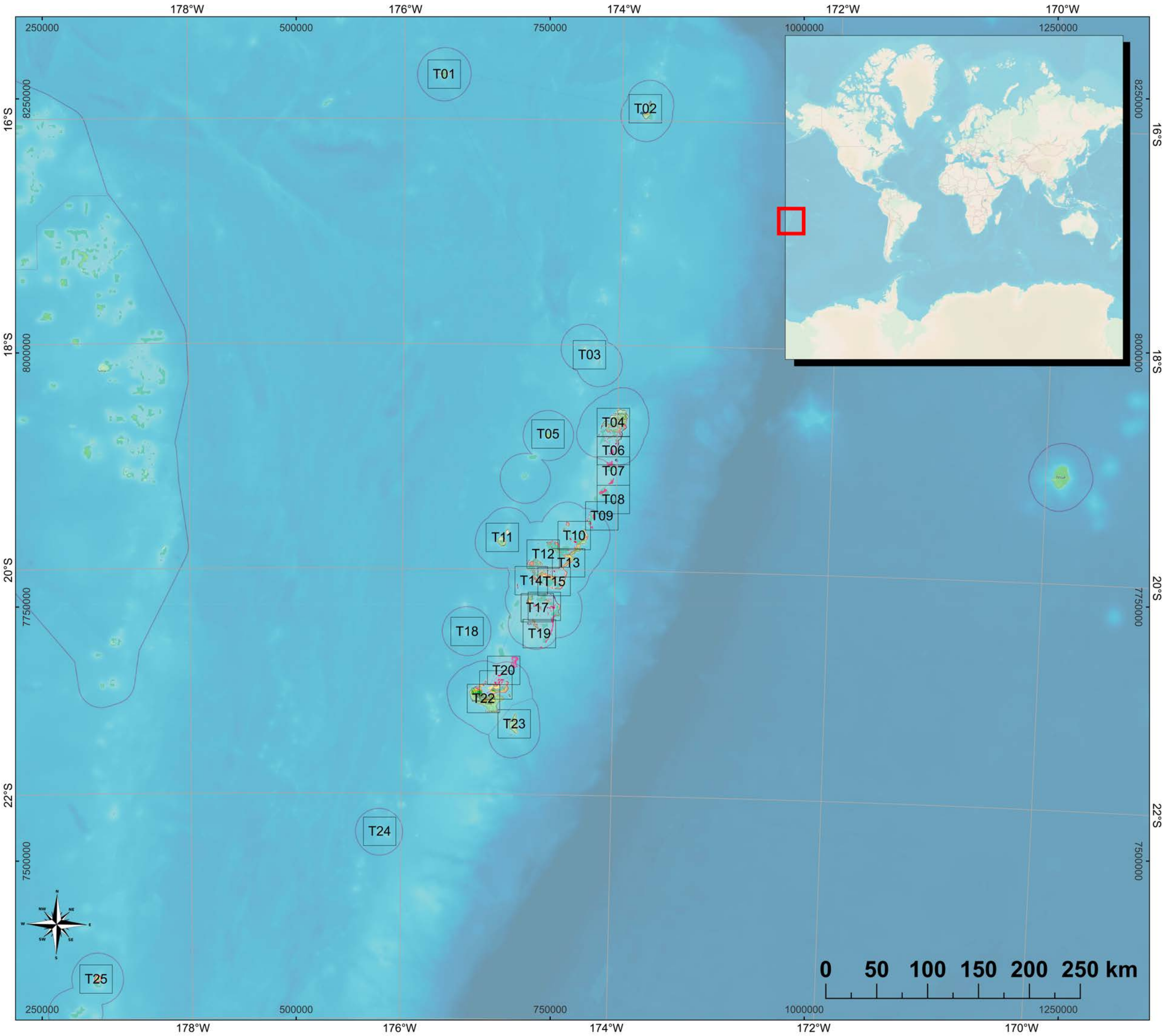
PeiranoA., Barsanti M., Delbono I., Candigliota E., Cocito S., Hokafonu T., Immordino F., Moretti L., Matoto A.L., 2023. “Baseline Assessment of Ecological Quality Index (EQI) of the Marine Coastal Habitats of Tonga Archipelago: Application for Management of Remote Regions in the Pacific” Remote Sensing 15, no. 4: 909. https://doi.org/10.3390/rs15040909

Reading guide to the Atlas

The Atlas reports 25 table referring to the habitat classification of corals, seagrasses and mangroves of the Tongan Archipelago at scale of 1:100.000. In each table is shown a map with a partial view of the Tonga Marine Habitat Mapping. Each habitat listed in the right of the table is shown on the map. The total Ecological Quality Index calculated for the area shown in the map is represented in the related pie chart. The Atlas is in electronic format, with shapefiles and database uploaded on Geographic Information System (QGIS) system. The Atlas is based on the photointerpretation of Sentinel-2 satellite images with 20 meters of resolution. Recognition of habitats were done on the basis of the radiometric characteristics of images and on analysis of ancillary data obtained from photos and videos available on the web.

The satellite images have the limit of being obscured by clouds and have different degrees of illumination, which is why in some cases it was necessary to use two photos of the same area taken at different times. Furthermore, the satellite images cannot show clearly the limits of the some habitats in case of presence of turbid water or rough sea. Moreover, in tropical seas, the satellite images cannot ‘see’ beyond 30 meters in depth, hence the depth limits of some coral habitat as the Forereef and Reef Bank can be underestimated.

It should be kept in mind that the information derived from the Atlas is just a piece of a network of information that must be completed and corrected with appropriate sea truth checks and detailed surveys on the areas of interest. For this reason its reading and interpretation is limited to a maximum magnification scale of 1: 50,000.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176°W
174°W
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170°W
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500000
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1000000
1250000
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0 50 100 150 200 250 km

Table list

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

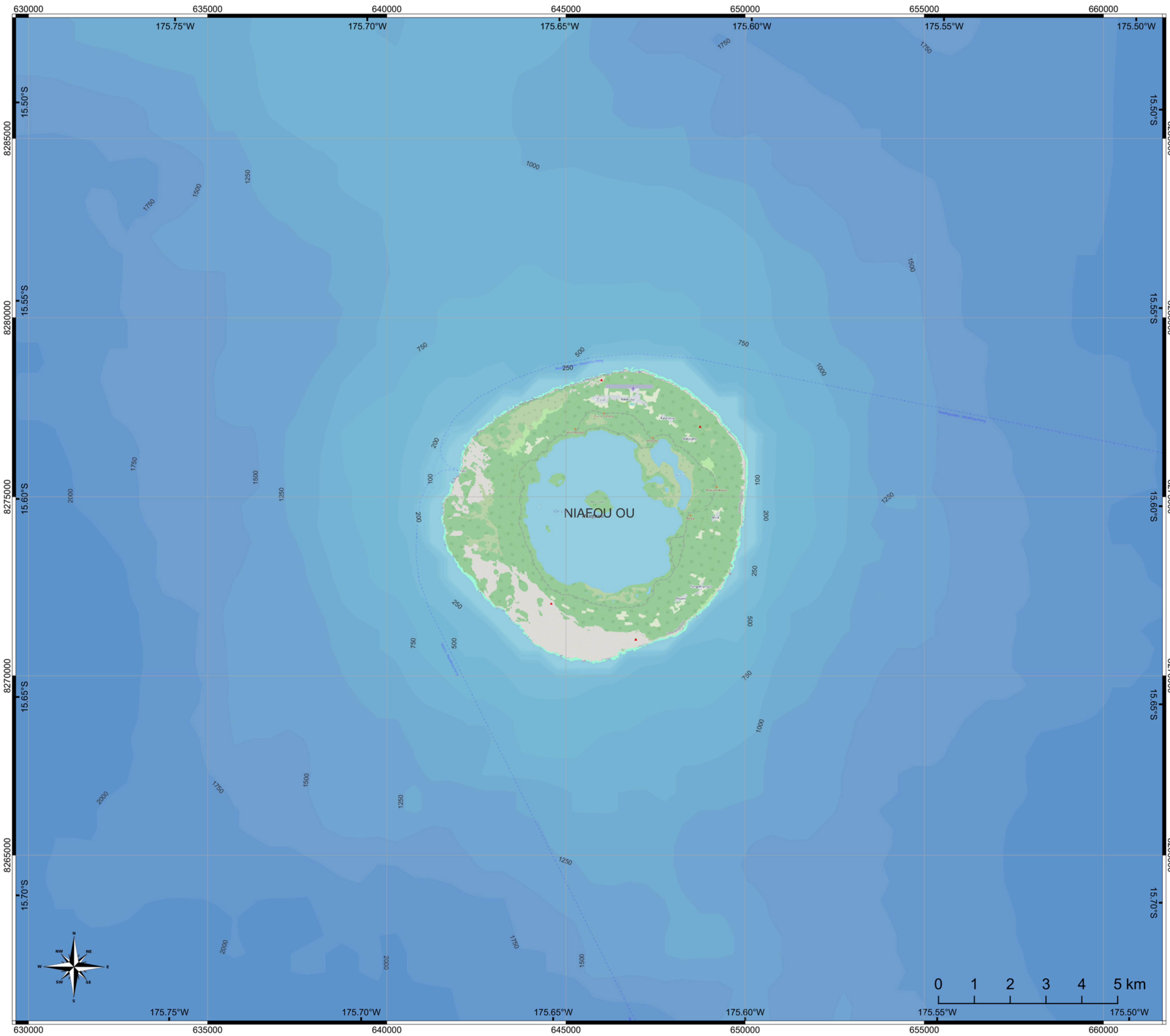

TABLE 1 OF 25 - T01

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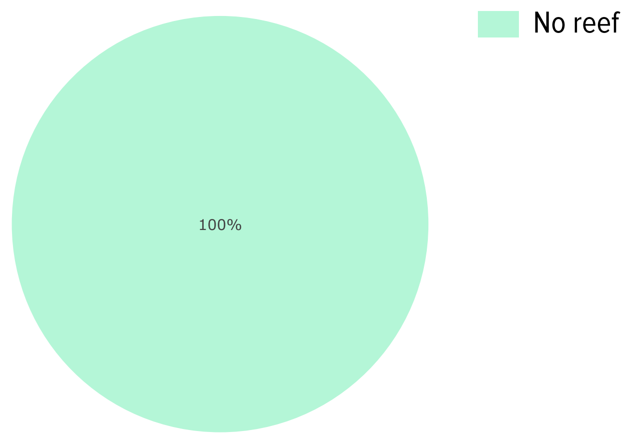
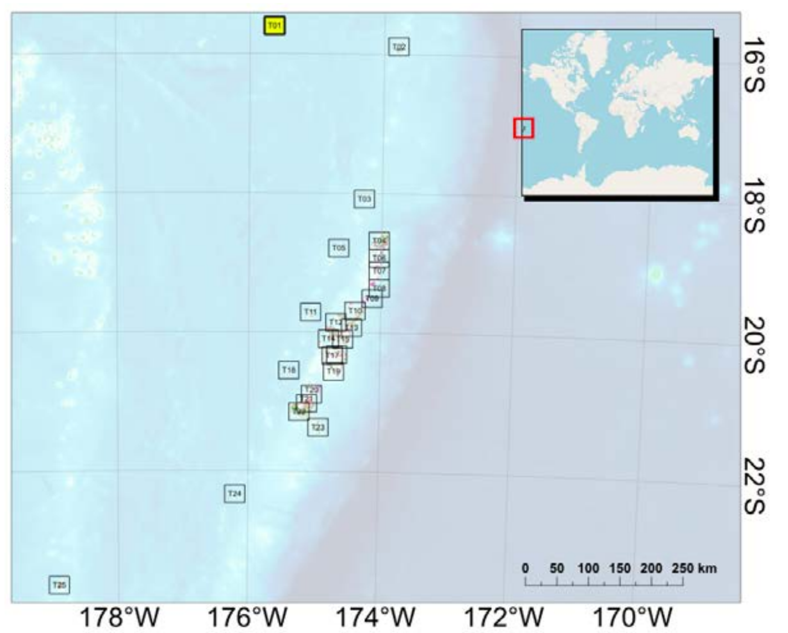
MARINE HABITATS





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Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

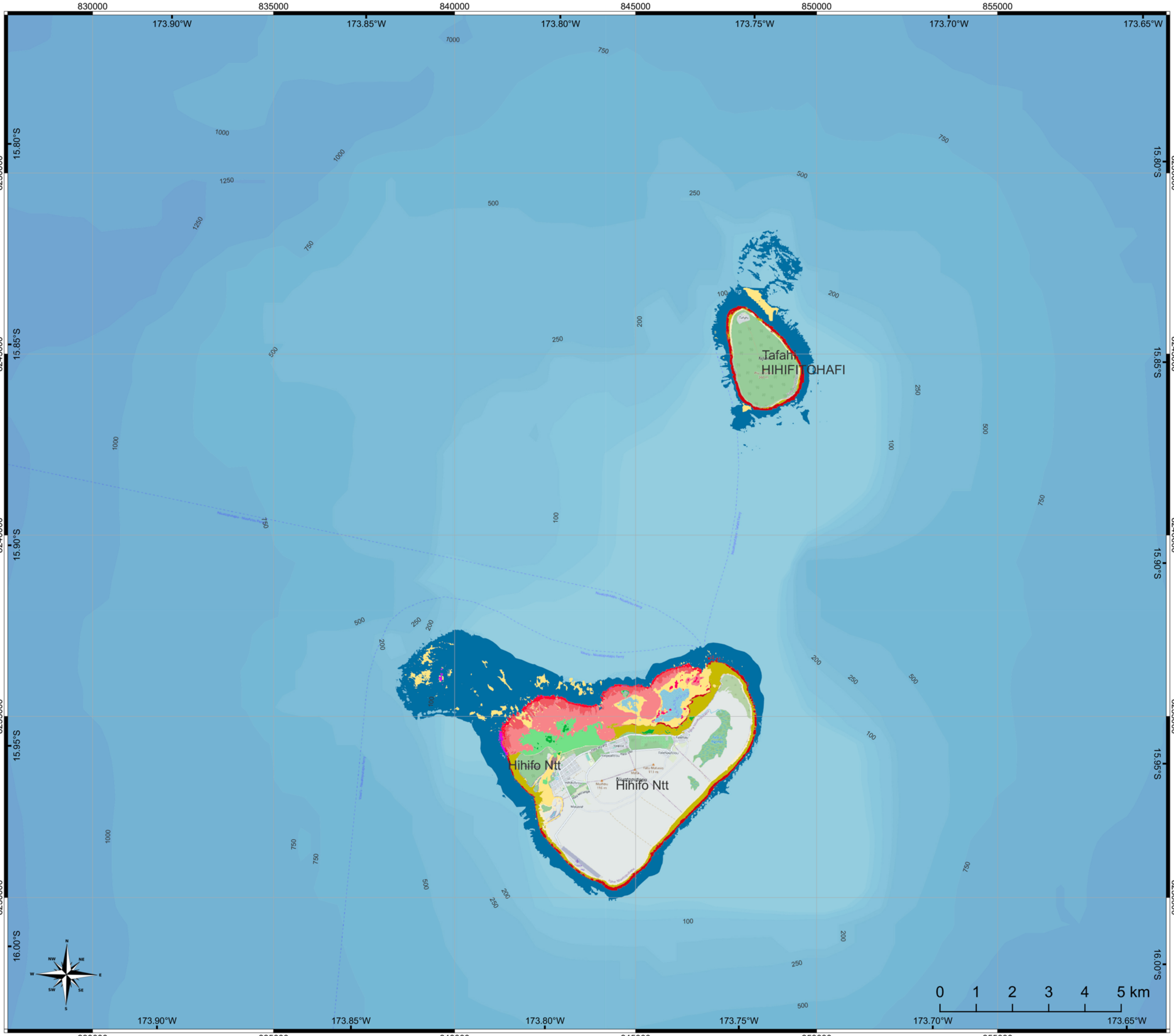

TABLE 2 OF 25 - T02

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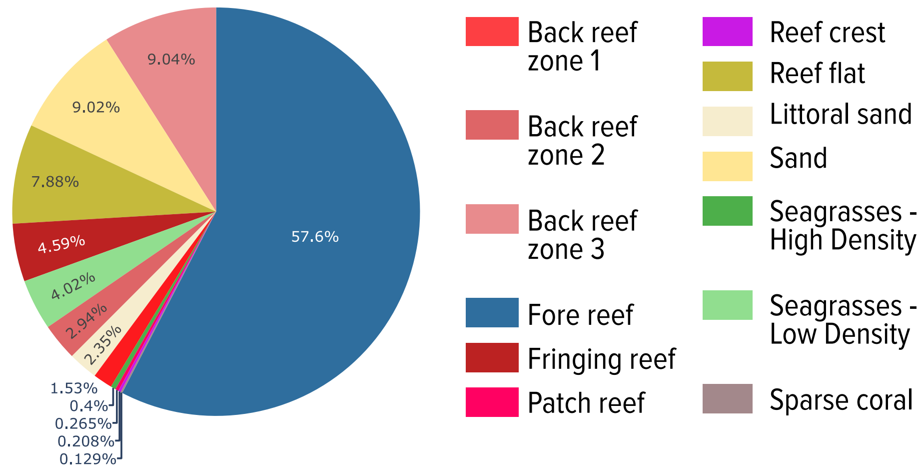
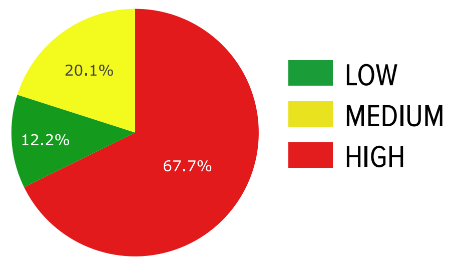
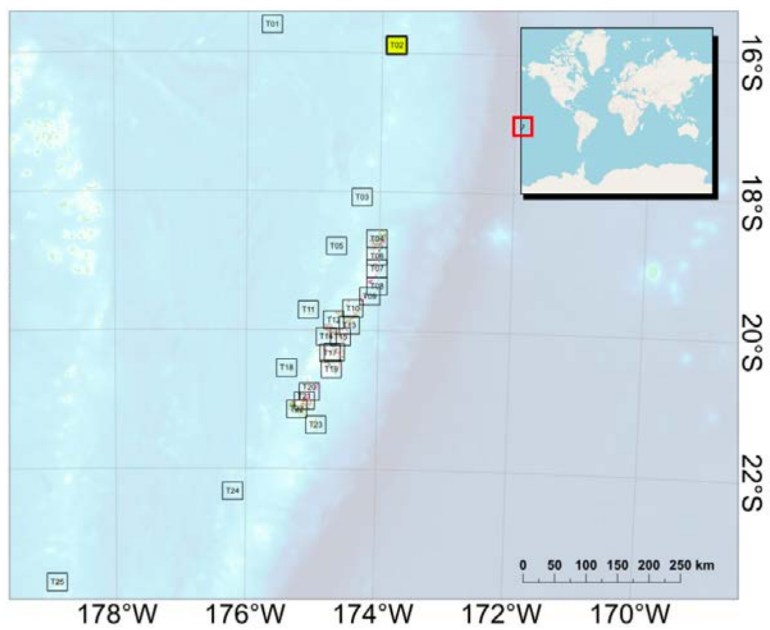


ECOLOGICAL QUALITY INDEX





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Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

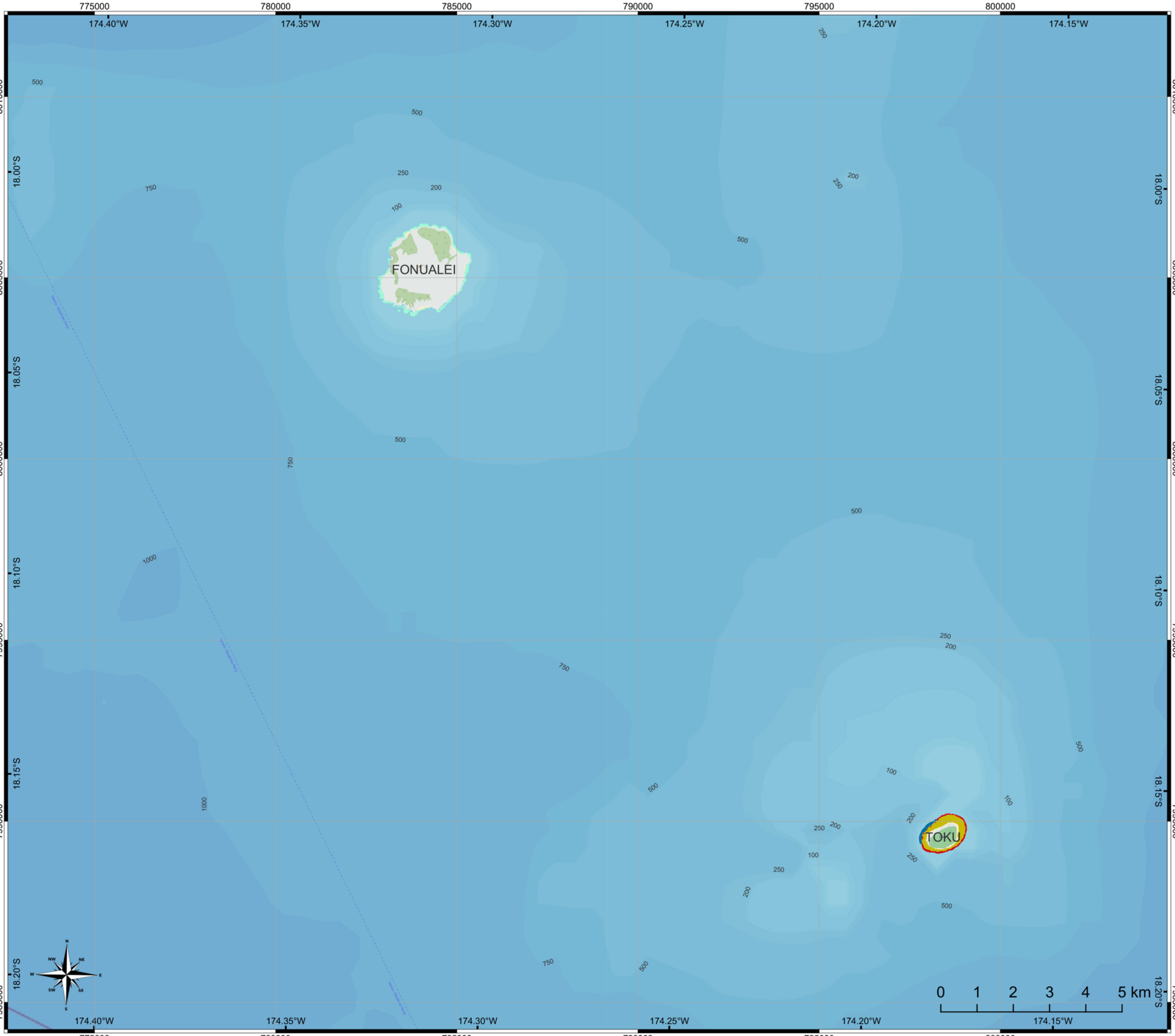

TABLE 3 OF 25 - T03

SCALE 1:100,000

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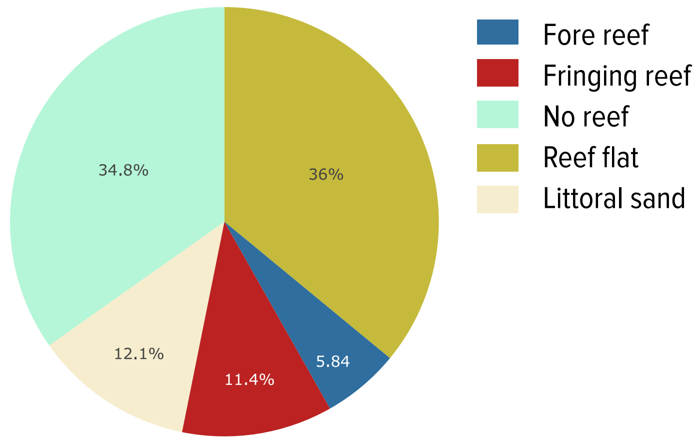
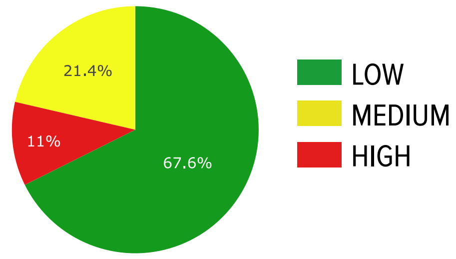
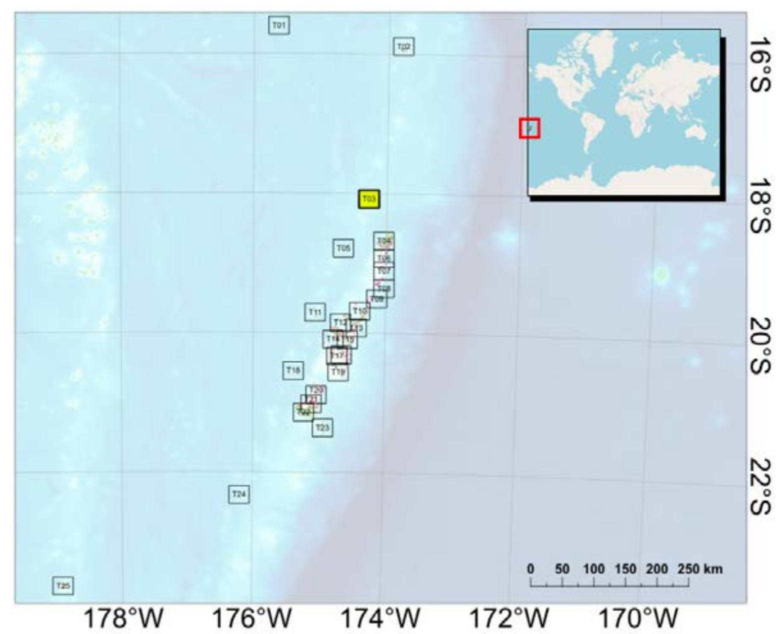


ECOLOGICAL QUALITY INDEX





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Remote Sensing Image: Sentinel-2 (years 2018-2019)

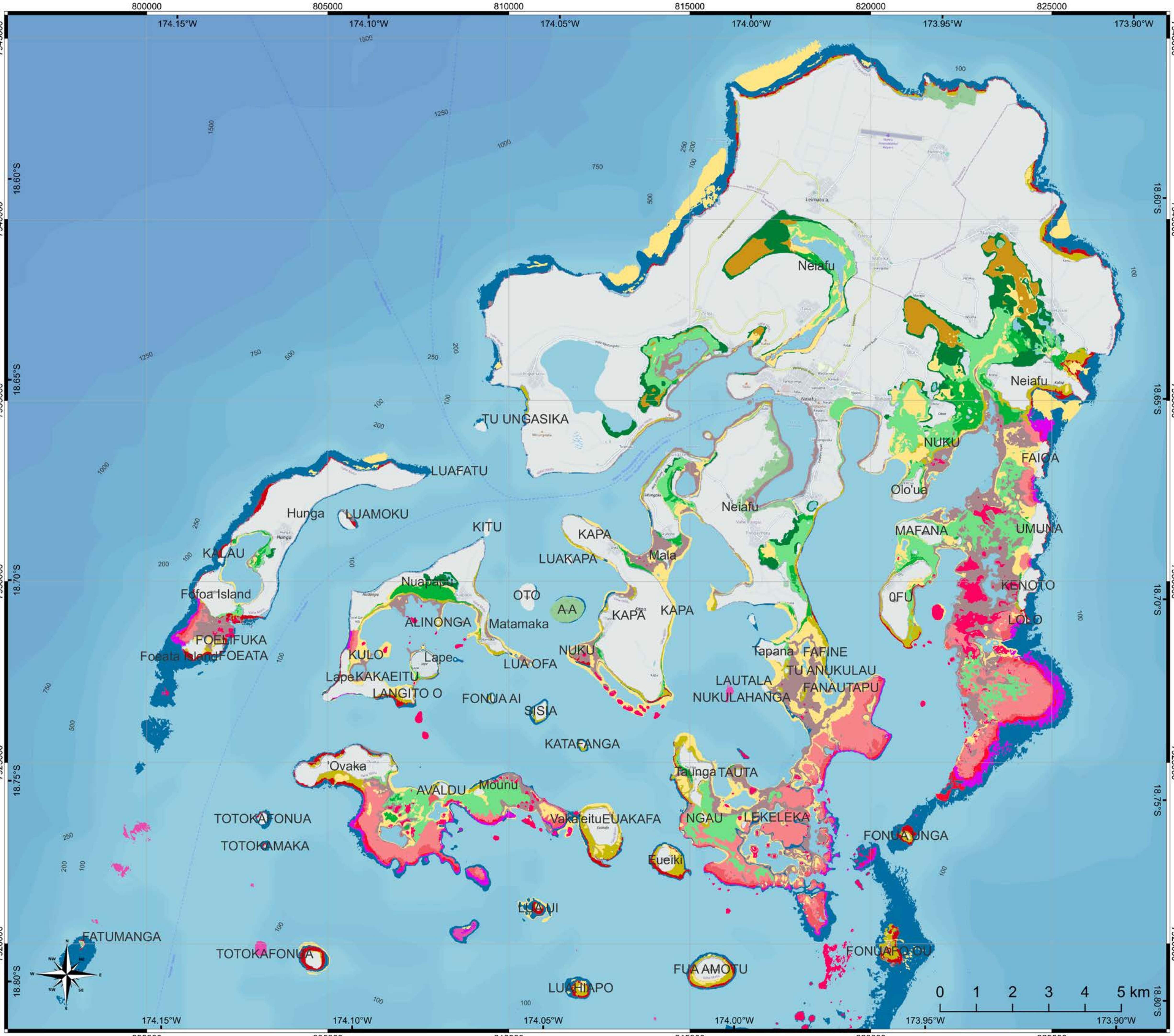

TABLE 4 OF 25 - T04

SCALE 1:100,000

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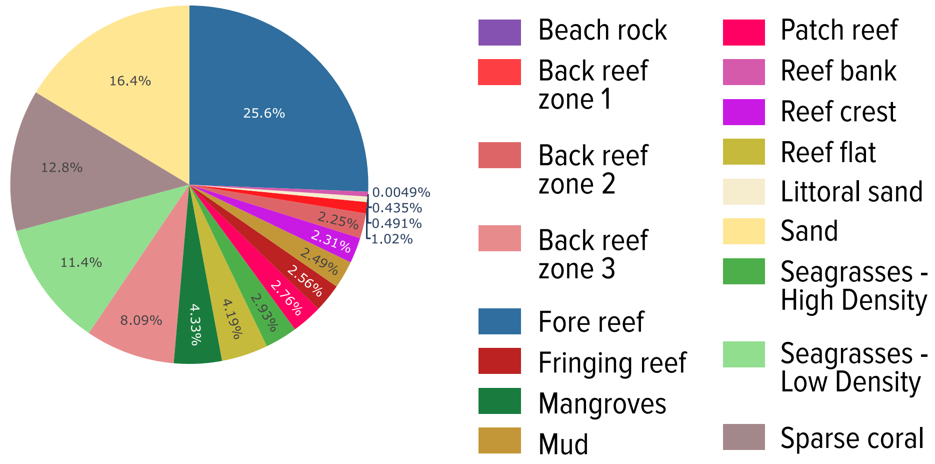
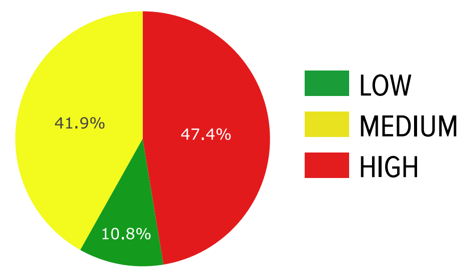
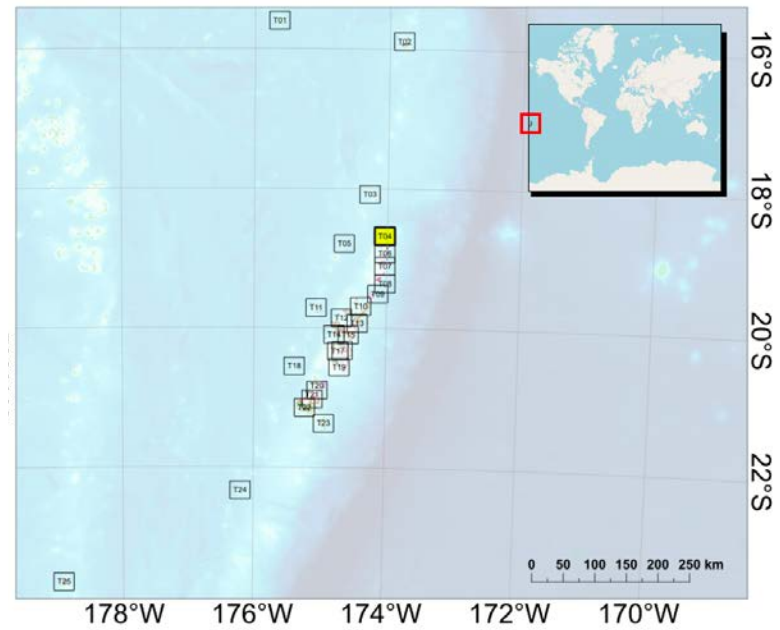


ECOLOGICAL QUALITY INDEX





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Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

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MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

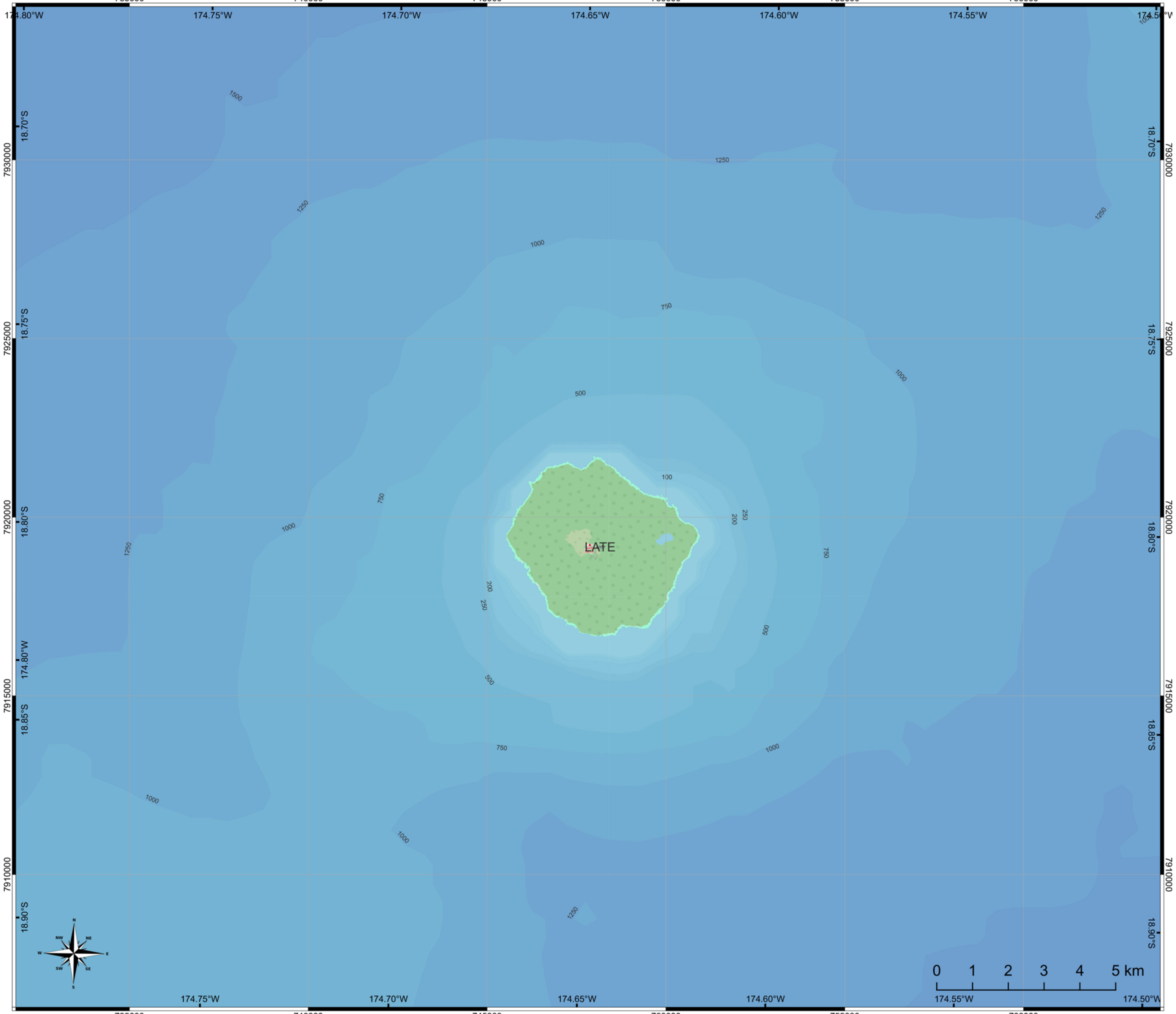

TABLE 5 OF 25 - T05

SCALE 1:100,000

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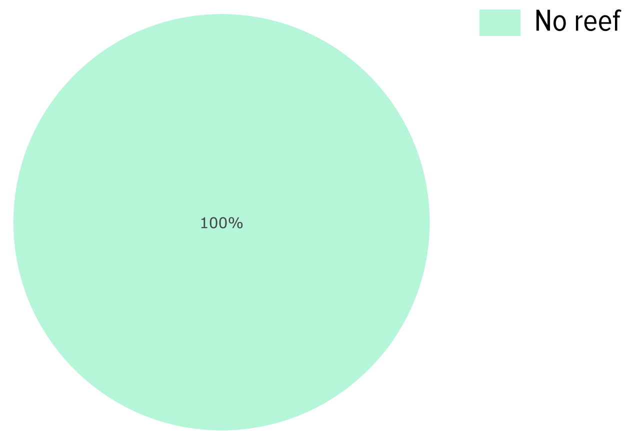

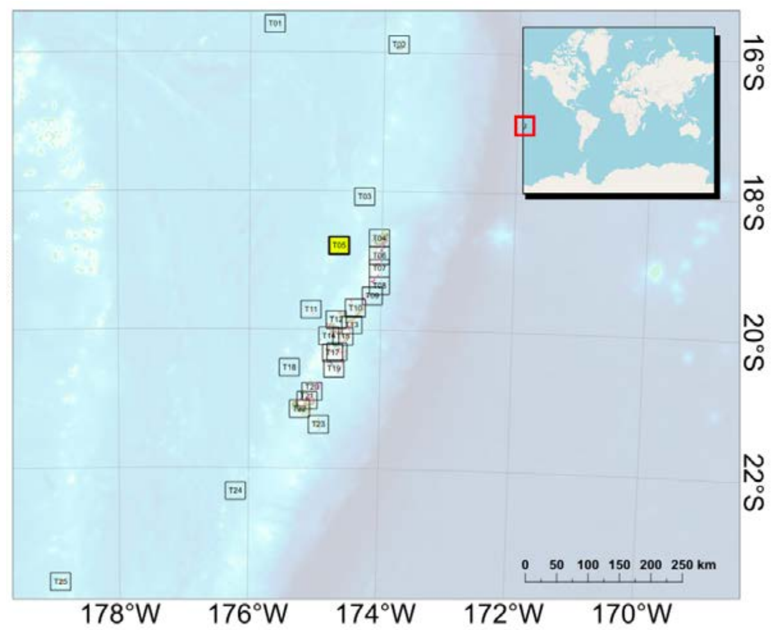

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Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

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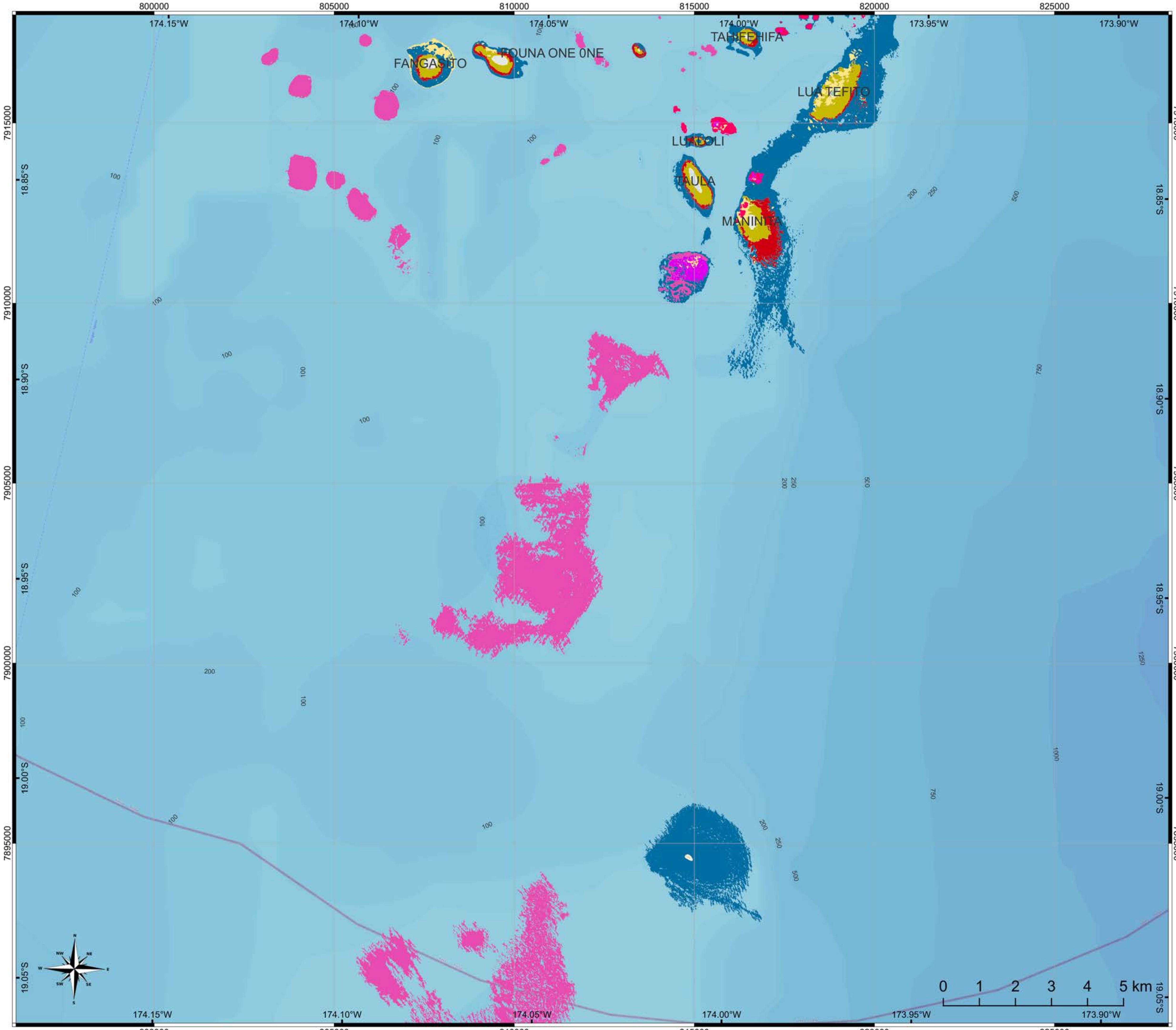

TABLE 6 OF 25 - T06

SCALE 1:100,000

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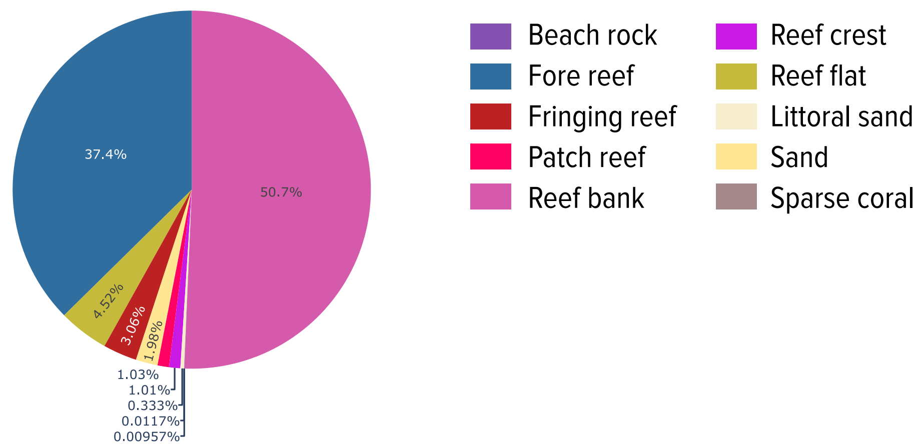

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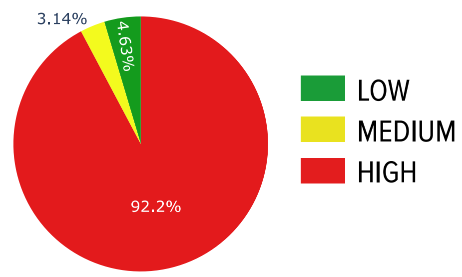

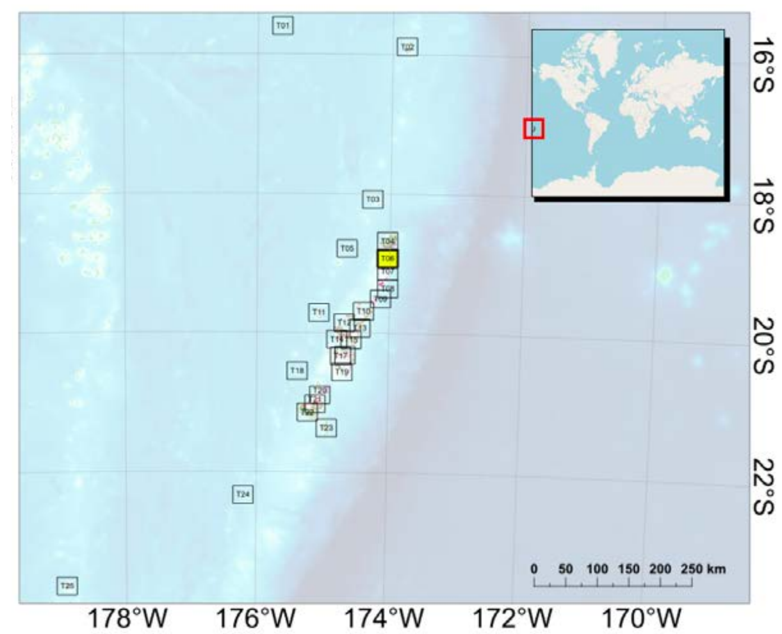

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Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

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MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

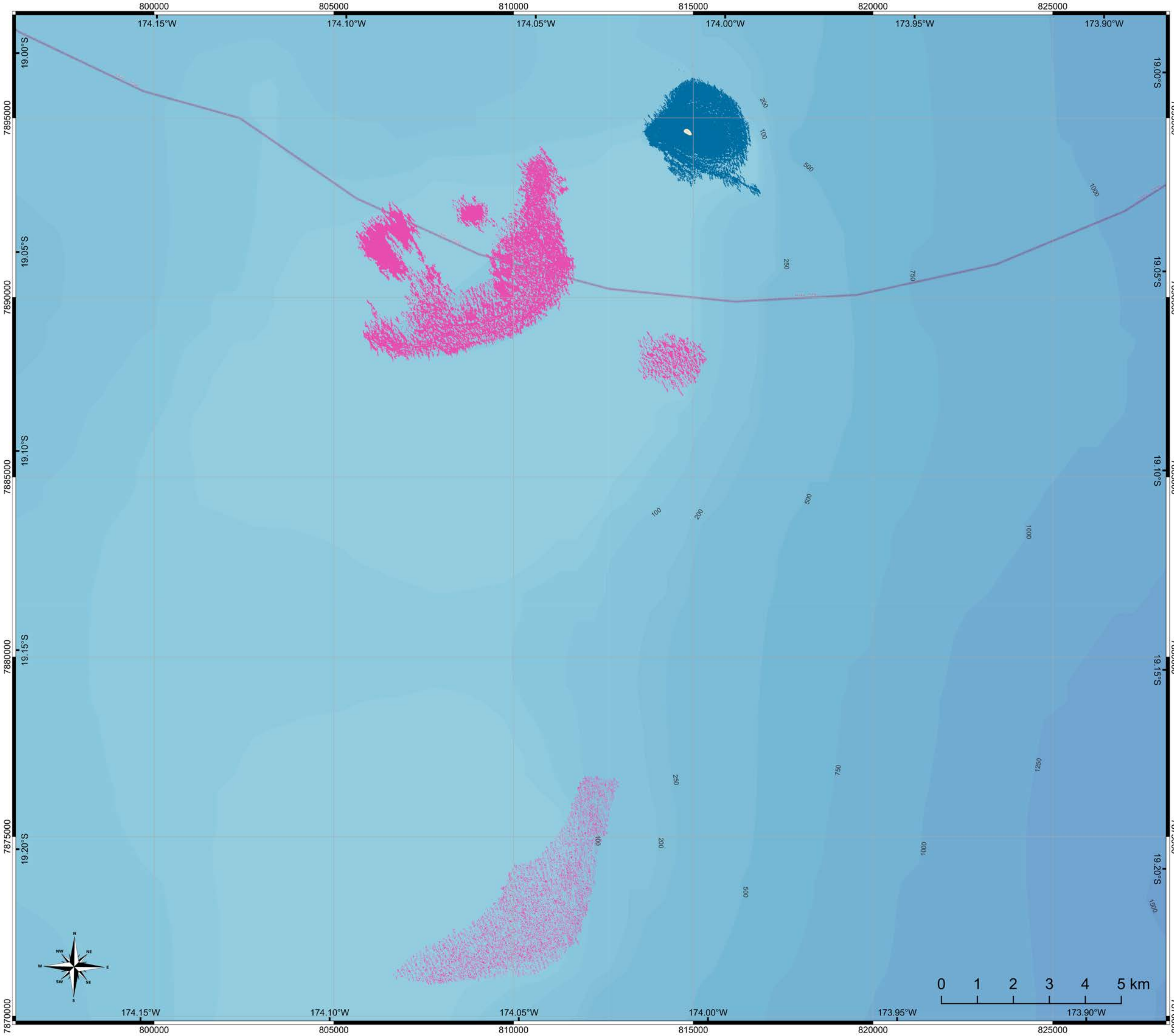

TABLE 7 OF 25 - T07

SCALE 1:100,000

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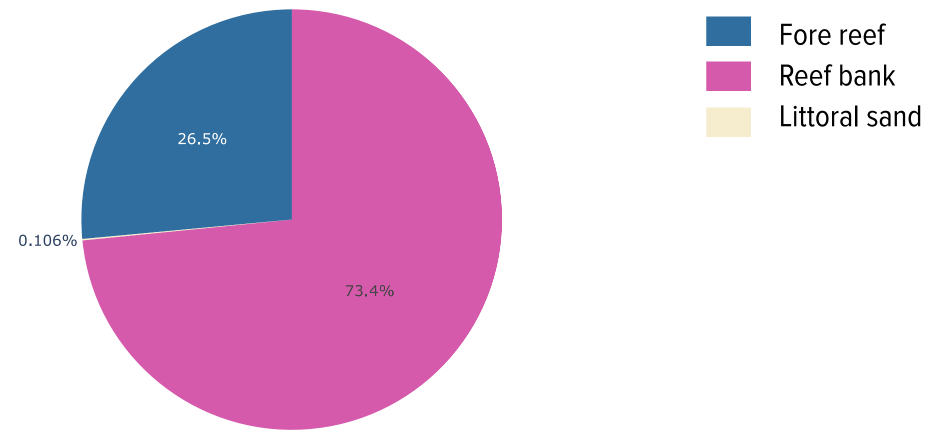

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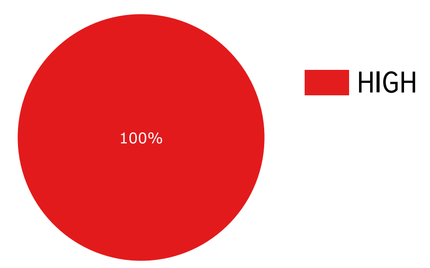

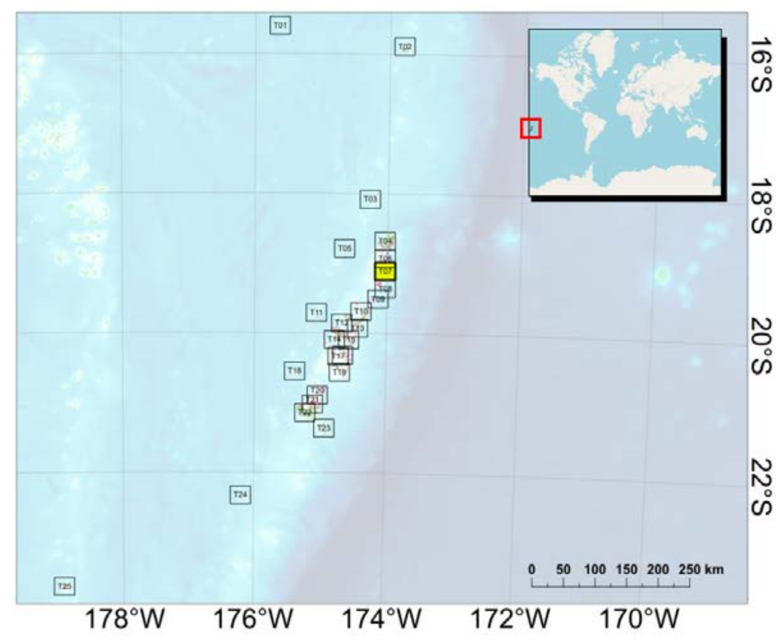

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Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

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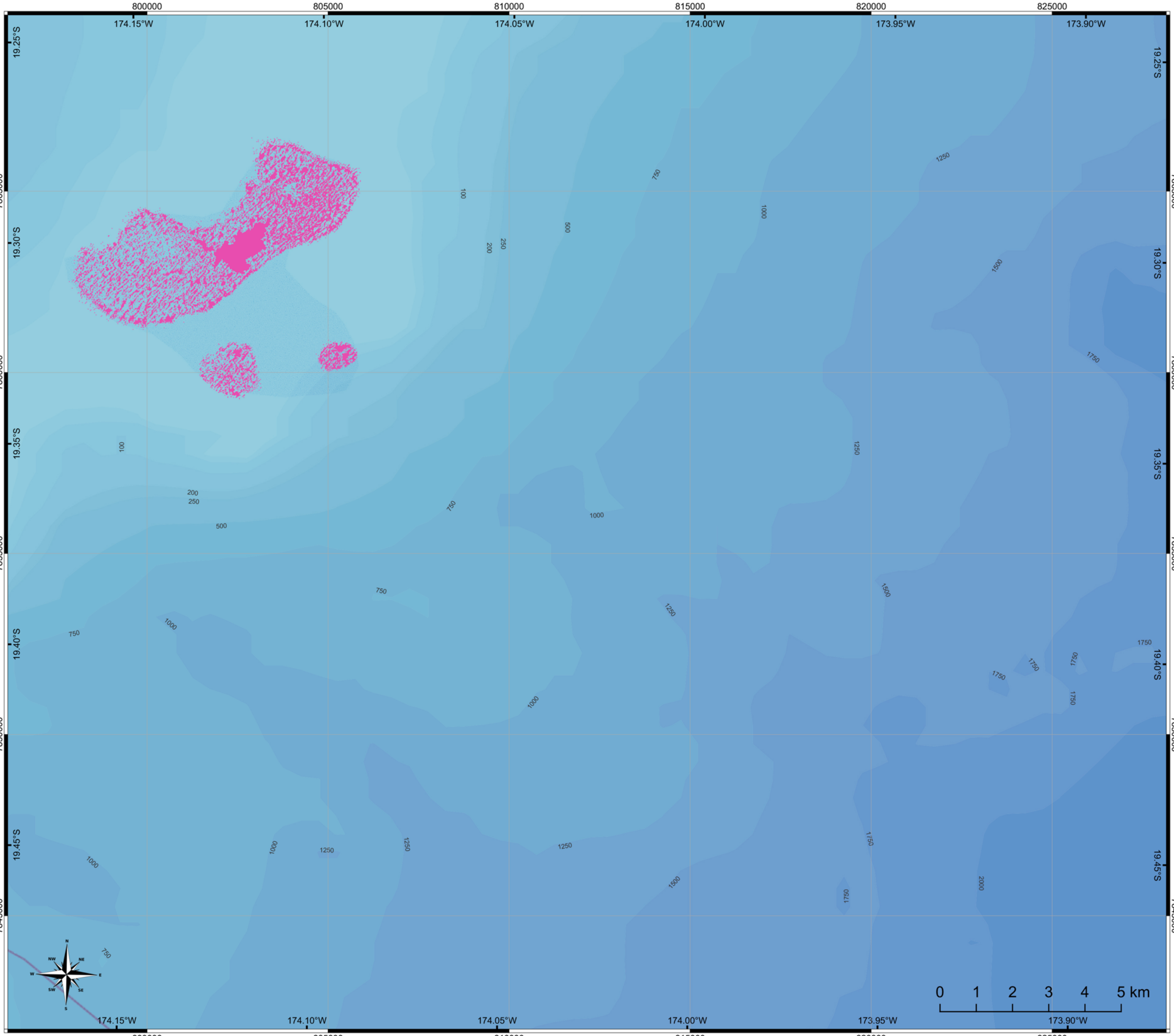

TABLE 8 OF 25 - T08

SCALE 1:100,000

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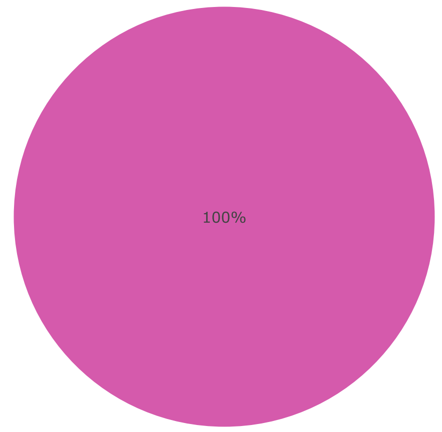

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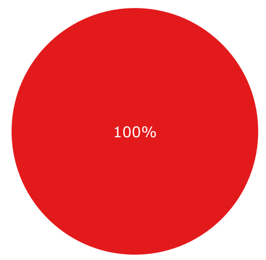

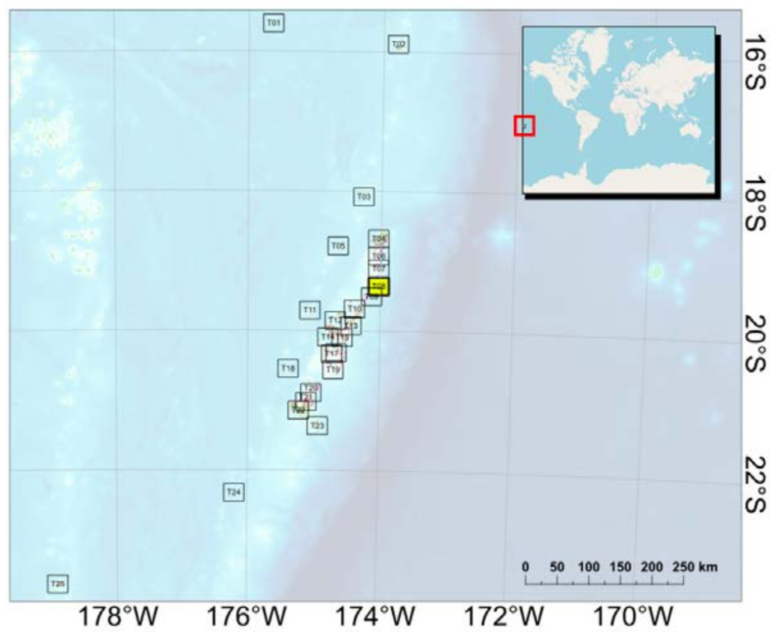

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Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

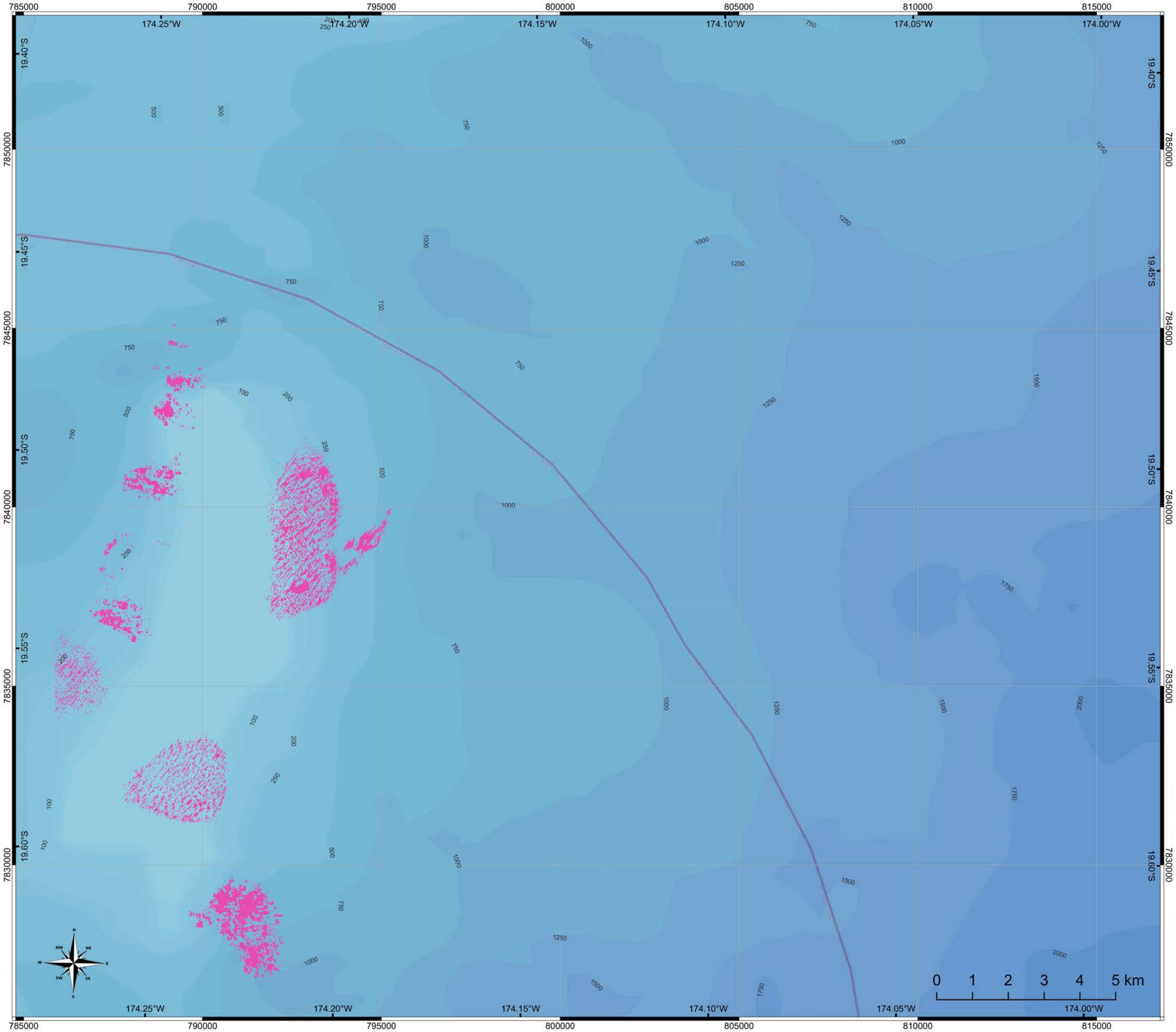

TABLE 9 OF 25 - T09
SCALE 1:100,000

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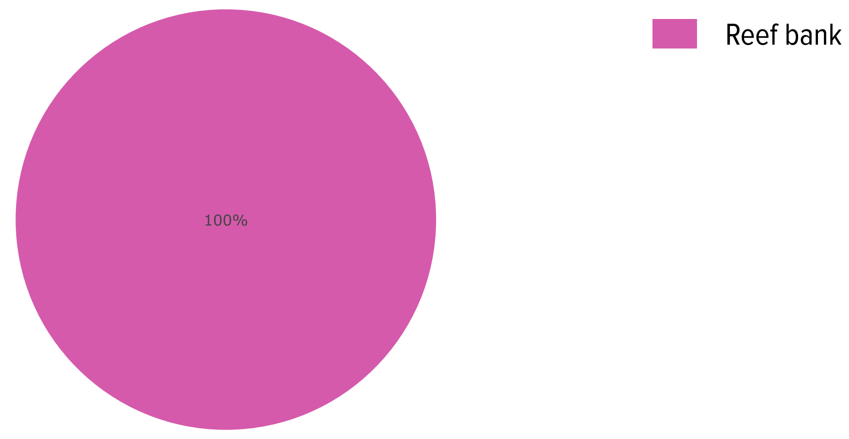

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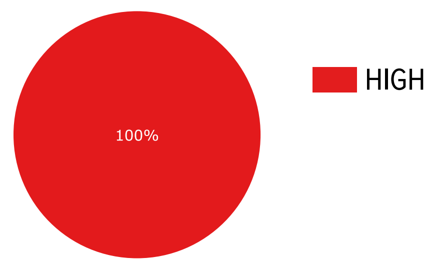

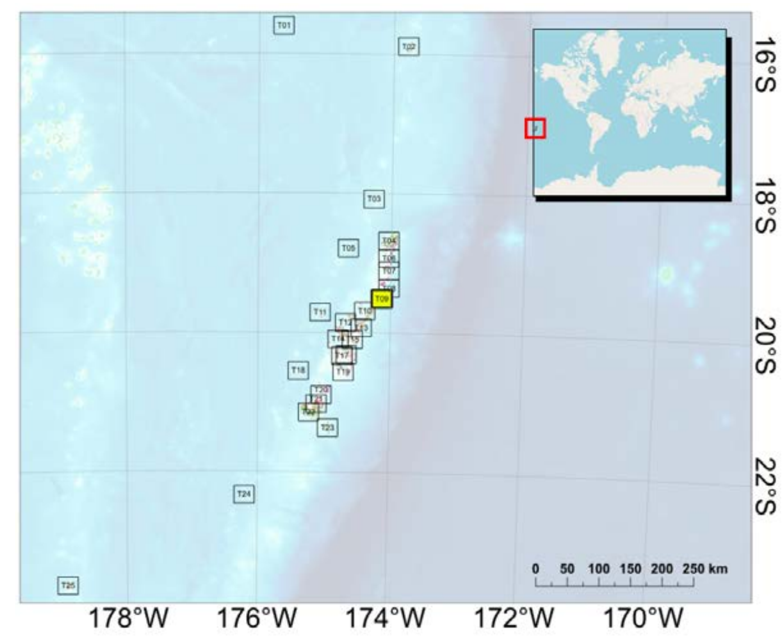

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Remote Sensing Image: Sentinel-2 (years 2018-2019)

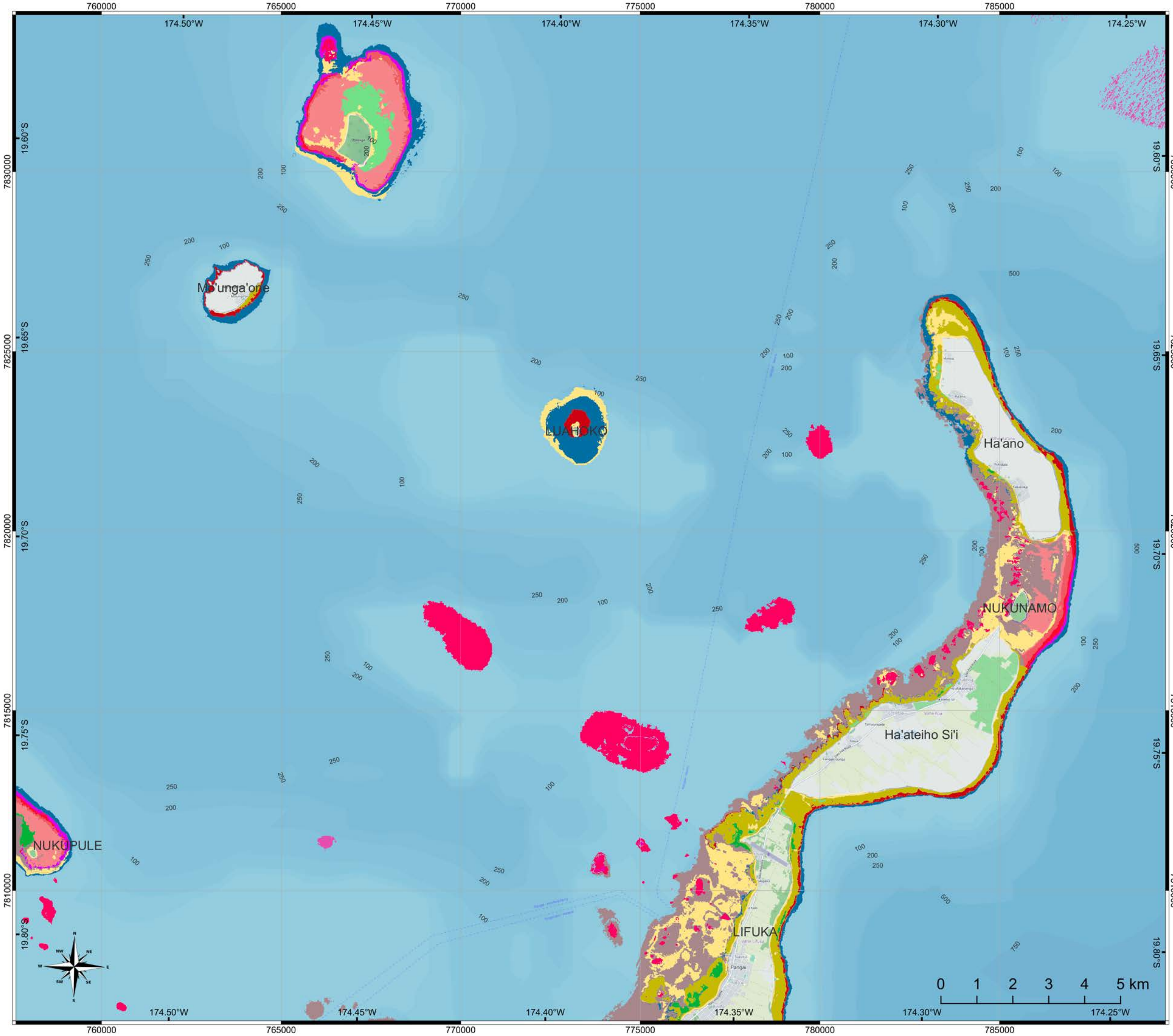

TABLE 10 OF 25 - T10

SCALE 1:100,000

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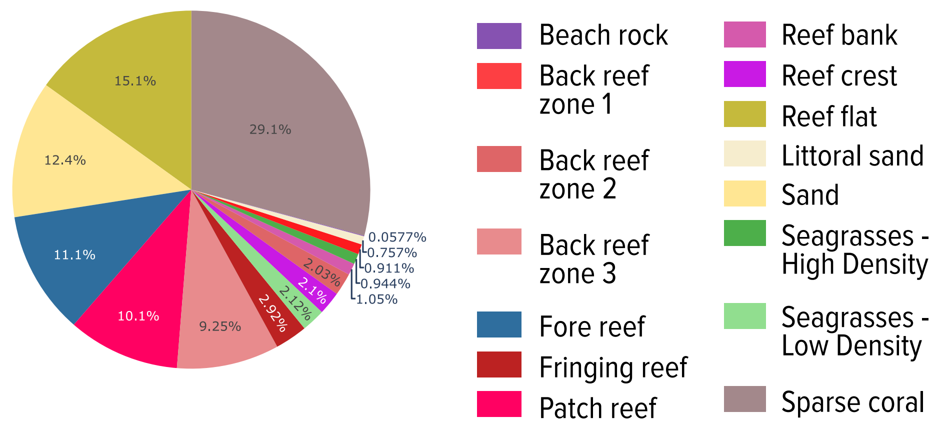

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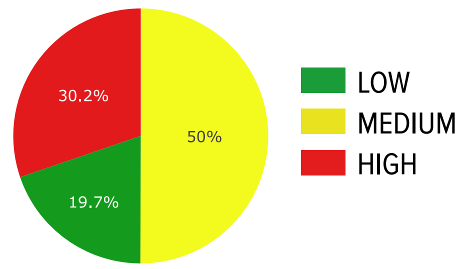

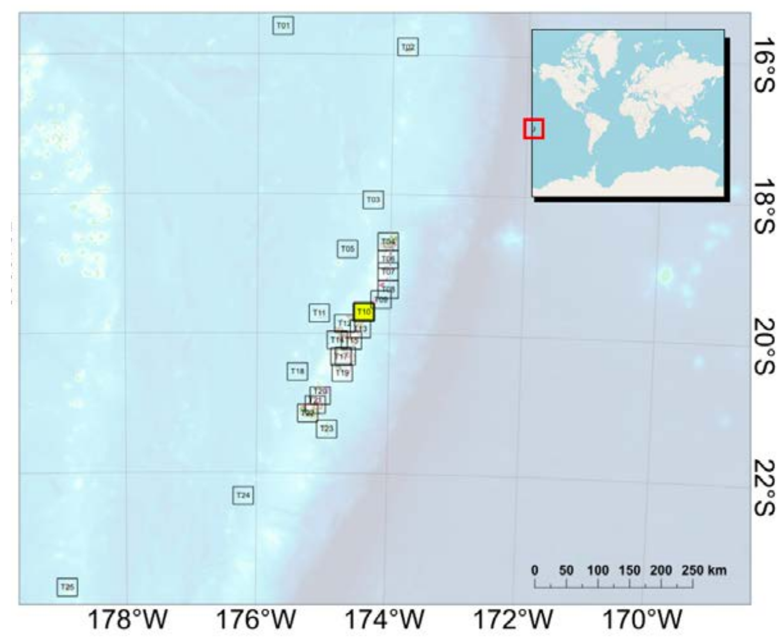

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ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

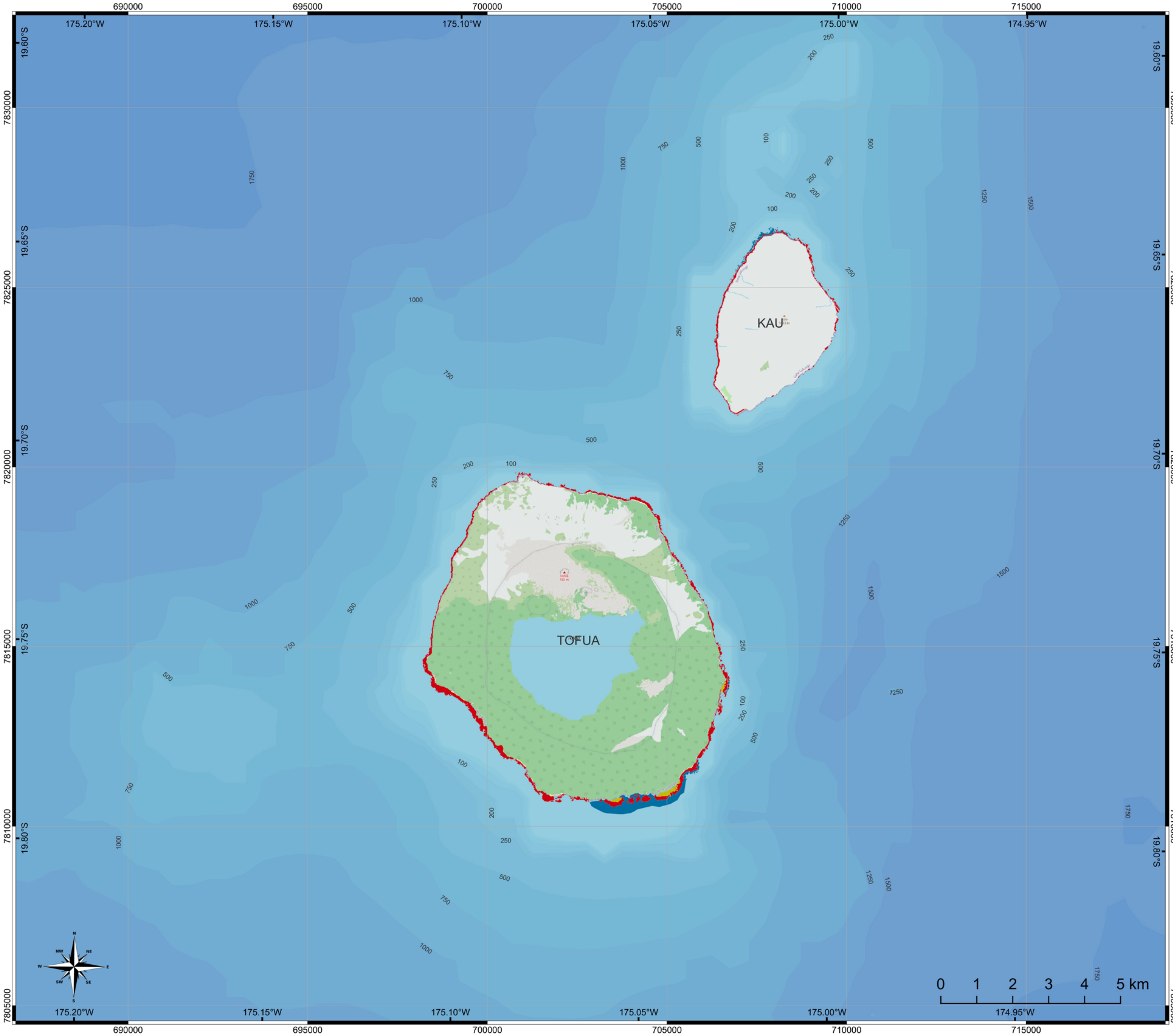
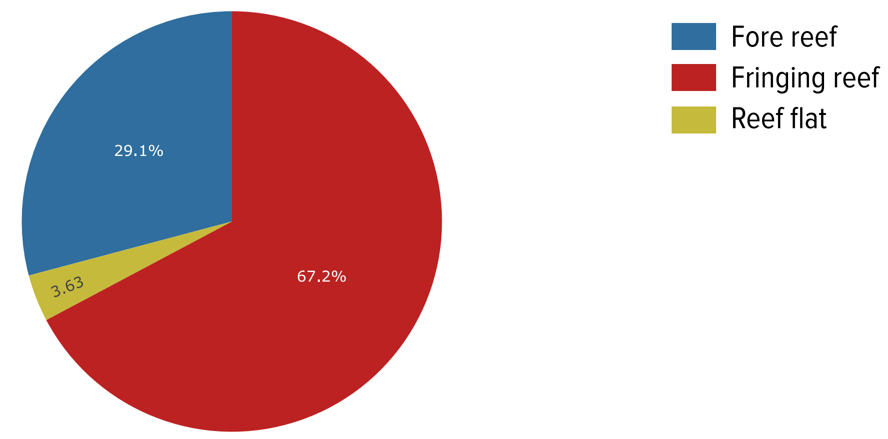


TABLE 11 OF 25 - T11

SCALE 1:100,000

MARINE HABITATS



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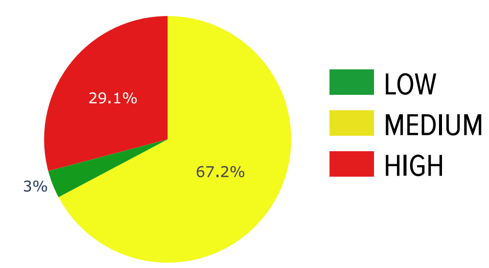

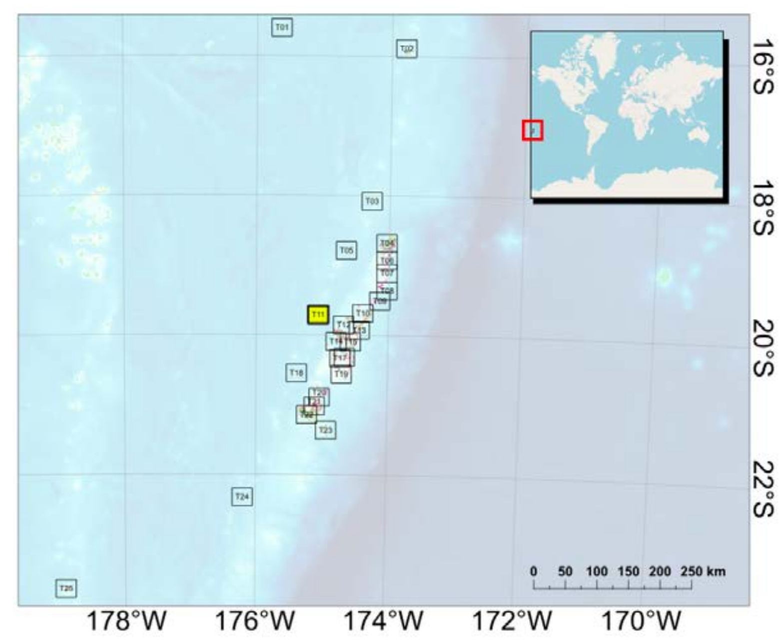

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Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

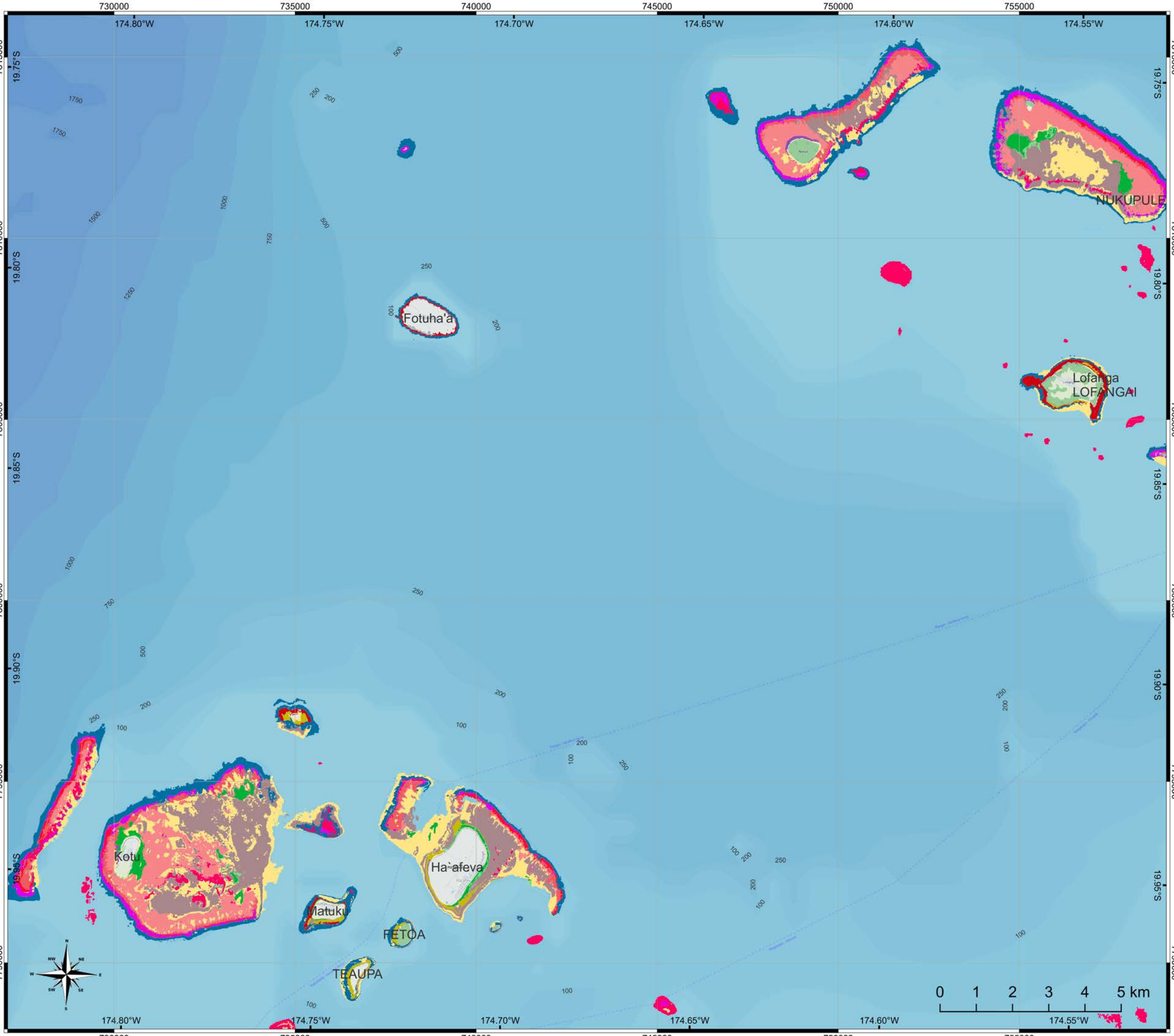
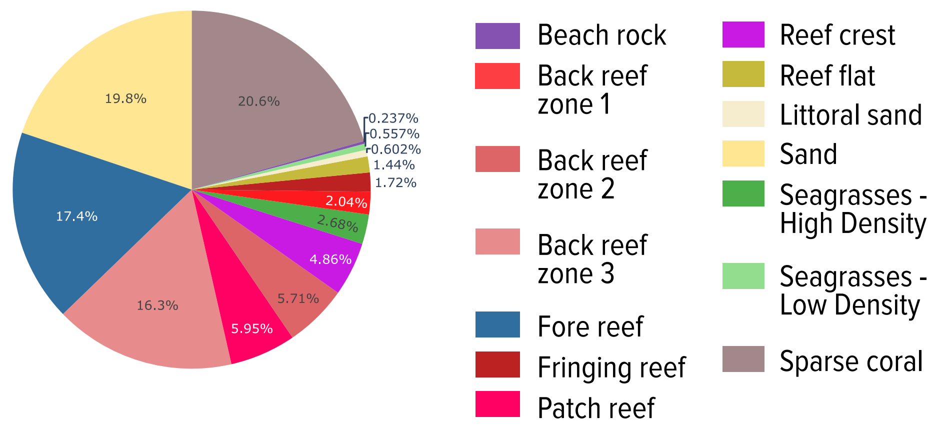


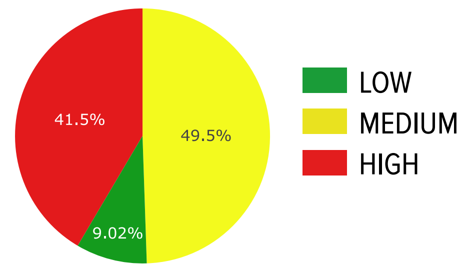
TABLE 12 OF 25 - T12

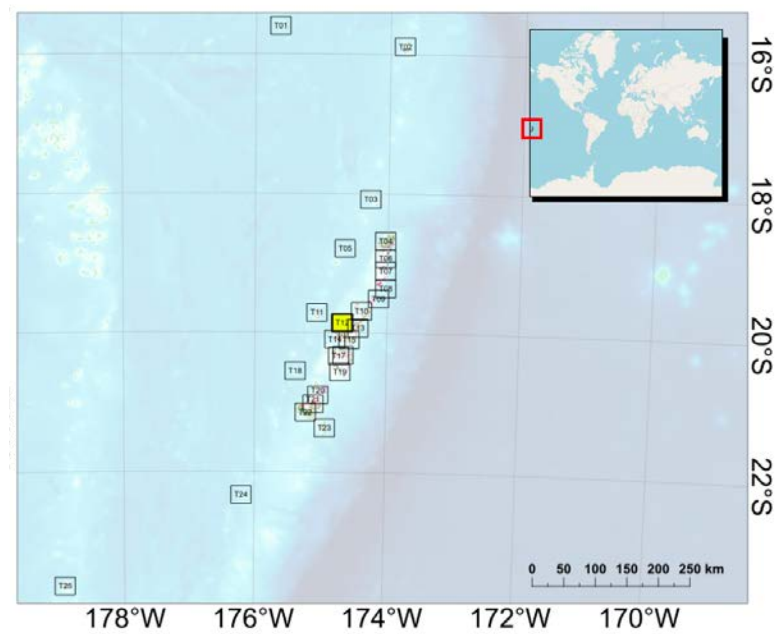
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

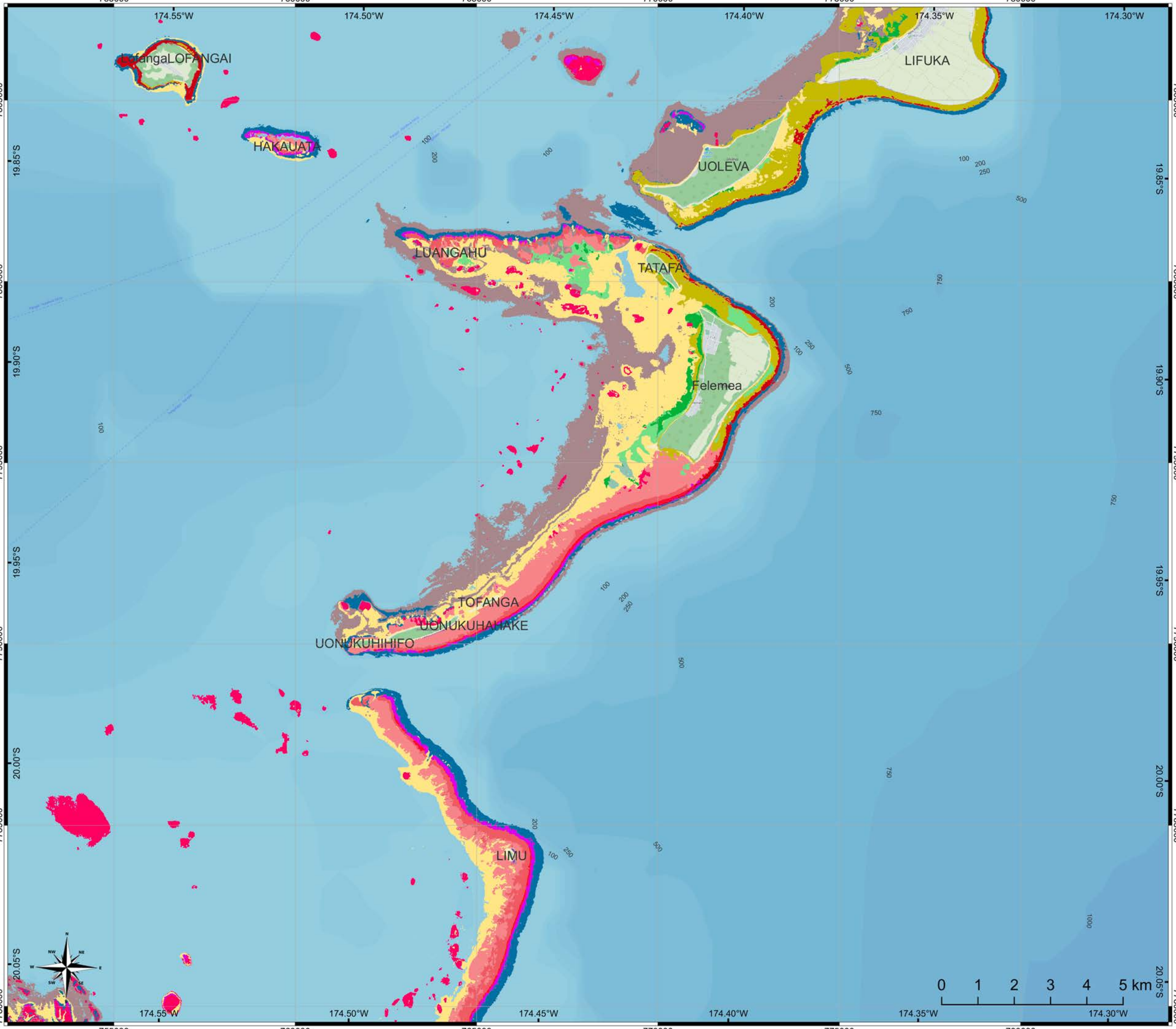
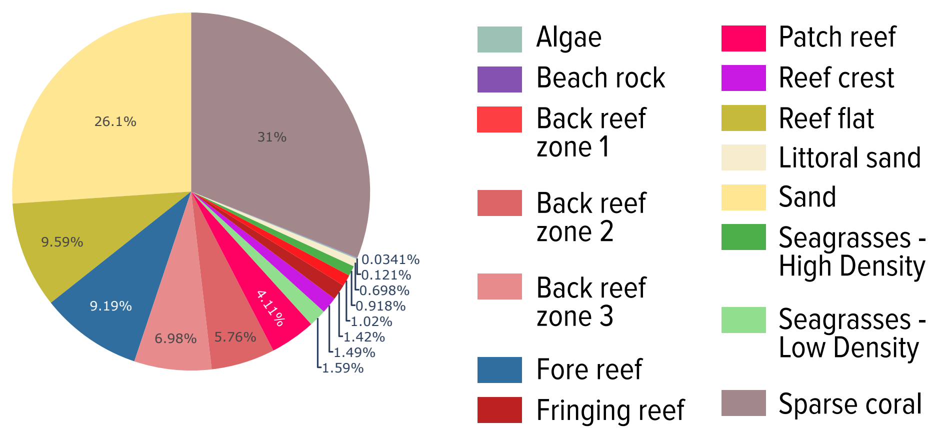


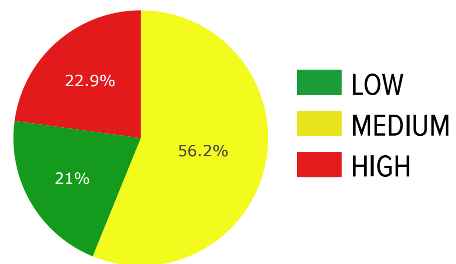
TABLE 13 OF 25 - T13

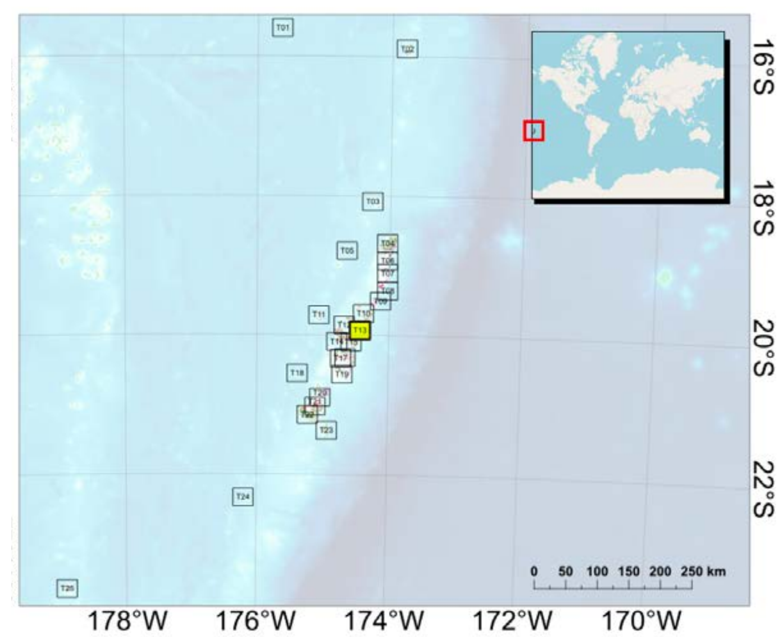
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

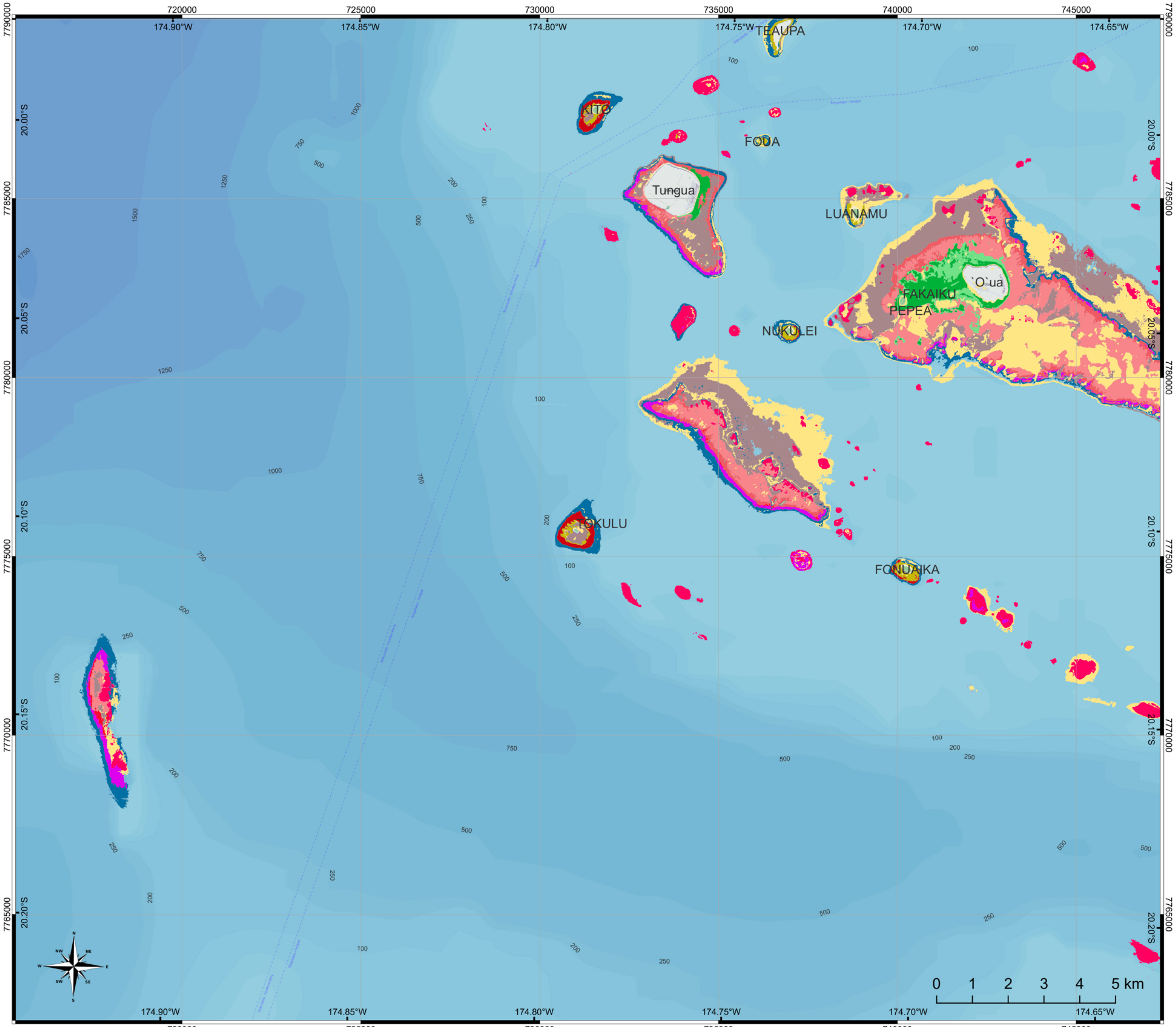
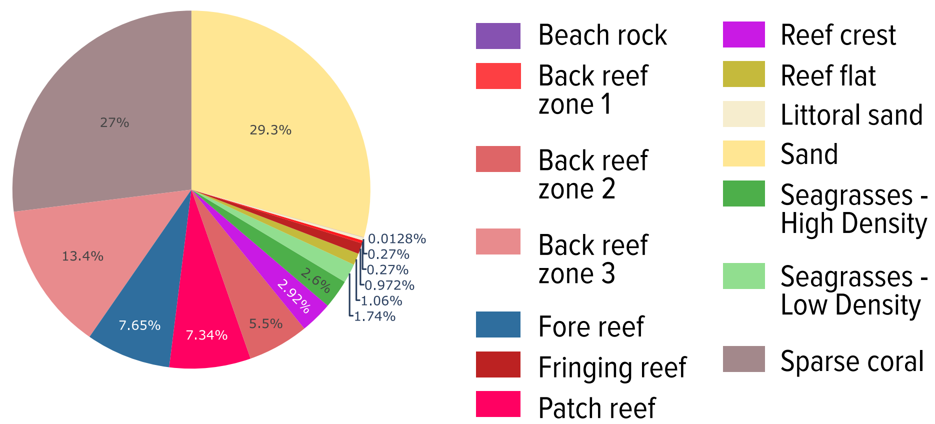


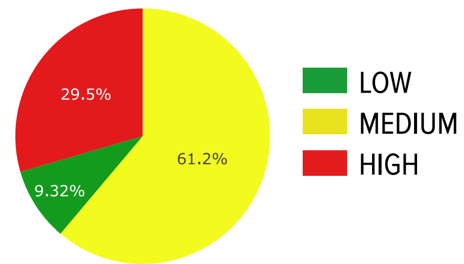
TABLE 14 OF 25 - T14

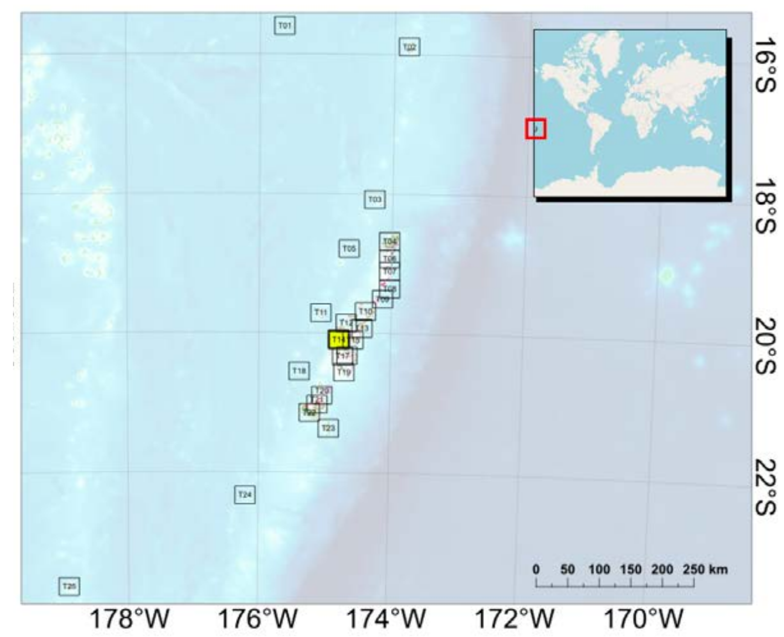
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT
MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

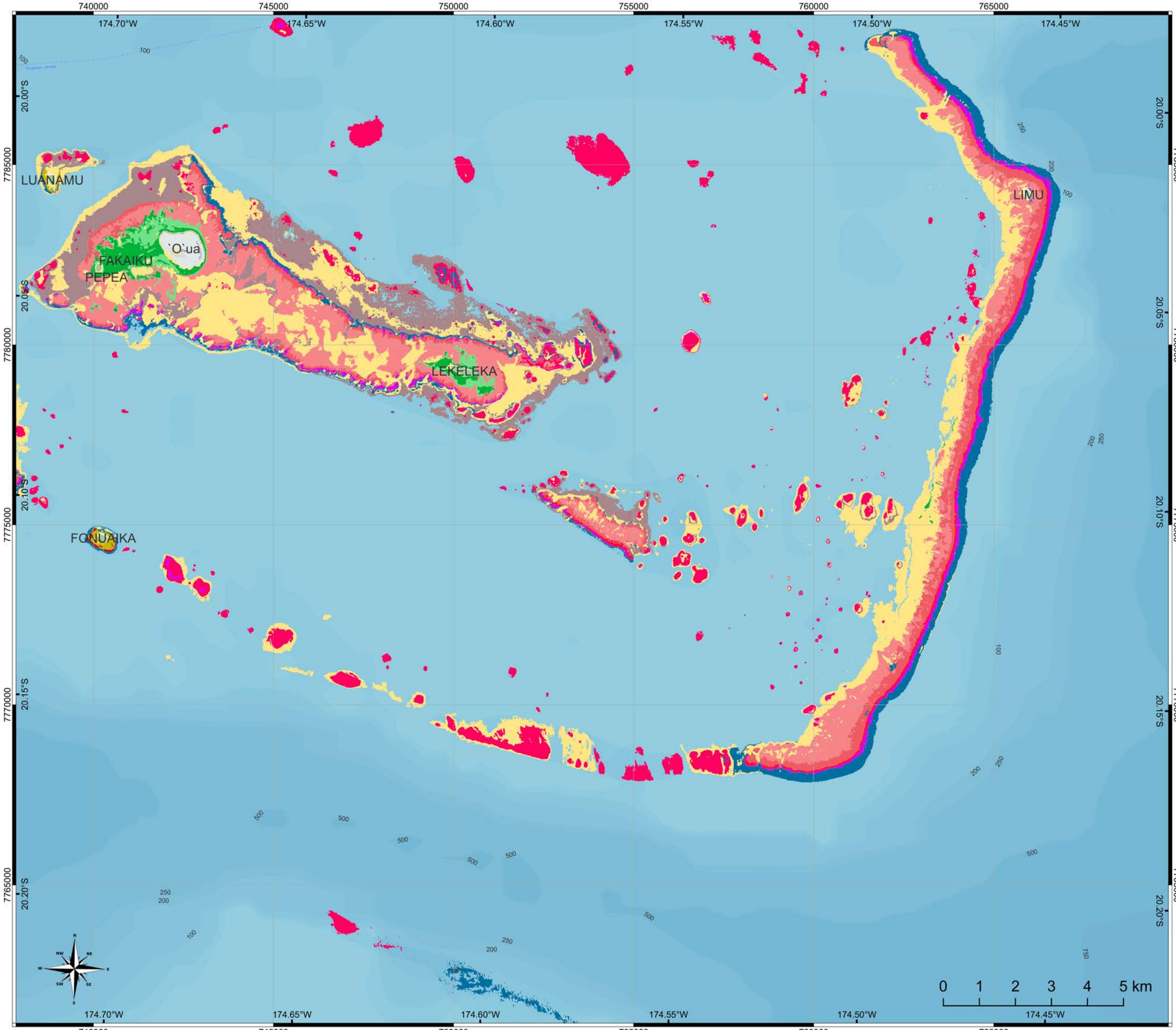
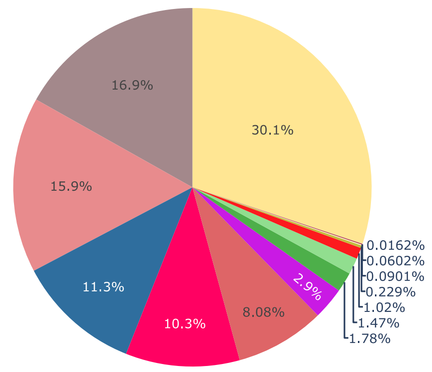


TABLE 15 OF 25 - T15

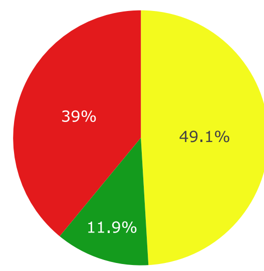
SCALE 1:100,000

MARINE HABITATS

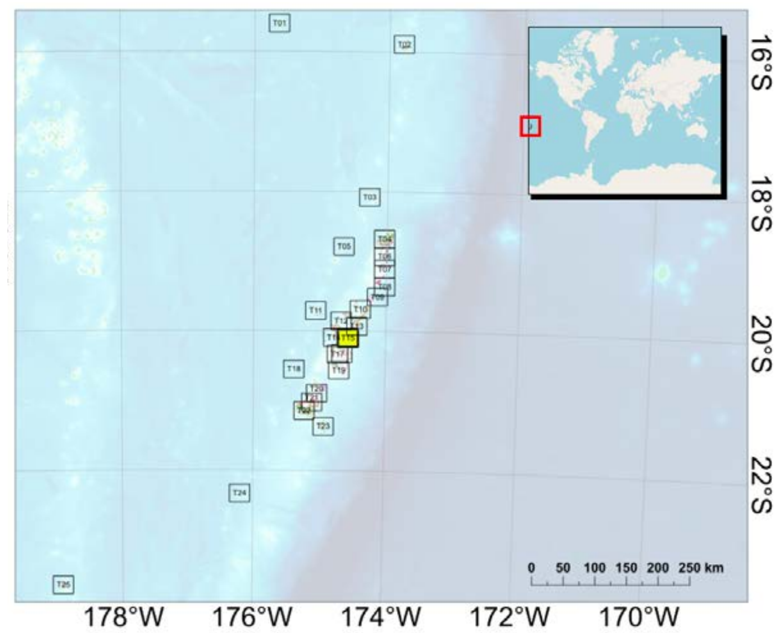


- Beach rock
- Back reef zone 1
- Back reef zone 2
- Back reef zone 3
- Fore reef
- Fringing reef
- Patch reef
- Reef crest
- Reef flat
- Littoral sand
- Sand
- Seagrasses - High Density
- Seagrasses - Low Density
- Sparse coral

ECOLOGICAL QUALITY INDEX



- LOW
- MEDIUM
- HIGH



Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

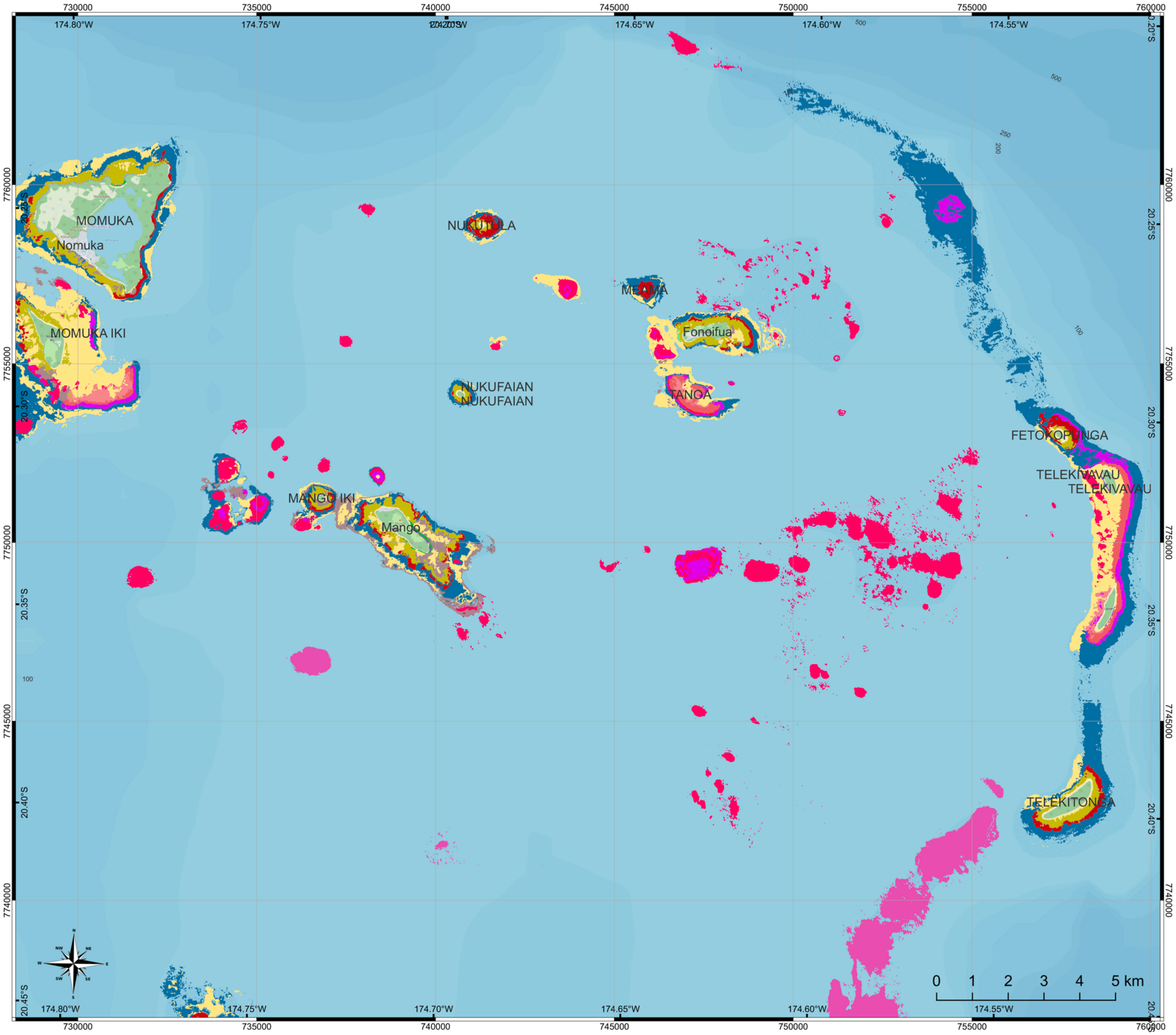
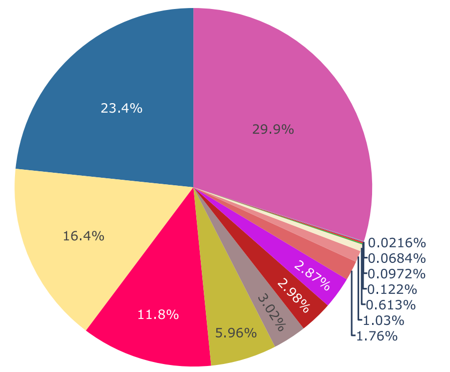


TABLE 16 OF 25 - T16

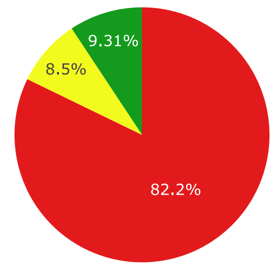
SCALE 1:100,000

MARINE HABITATS

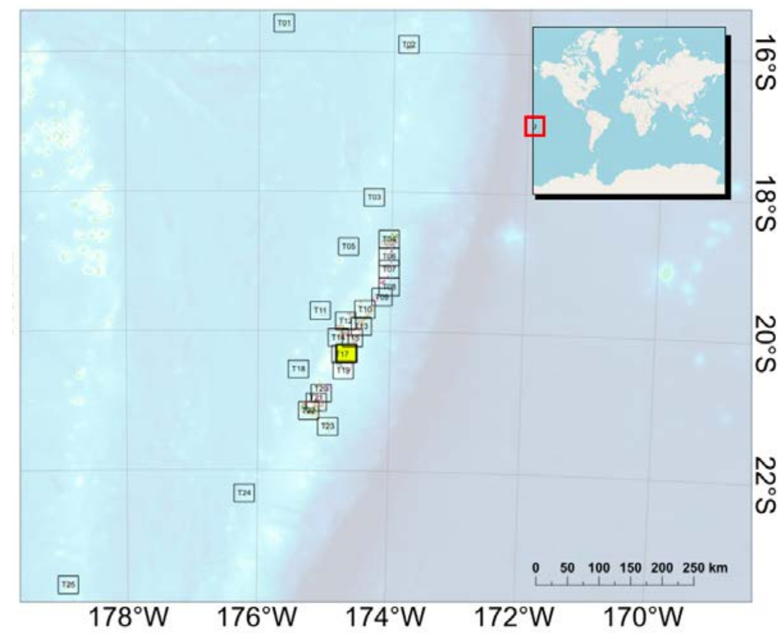


- Beach rock
- Back reef zone 1
- Back reef zone 2
- Back reef zone 3
- Fore reef
- Fringing reef
- Patch reef
- Reef bank
- Reef crest
- Reef flat
- Littoral sand
- Sand
- Seagrasses - High Density
- Seagrasses - Low Density
- Sparse coral

ECOLOGICAL QUALITY INDEX



- LOW
- MEDIUM
- HIGH



Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

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MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

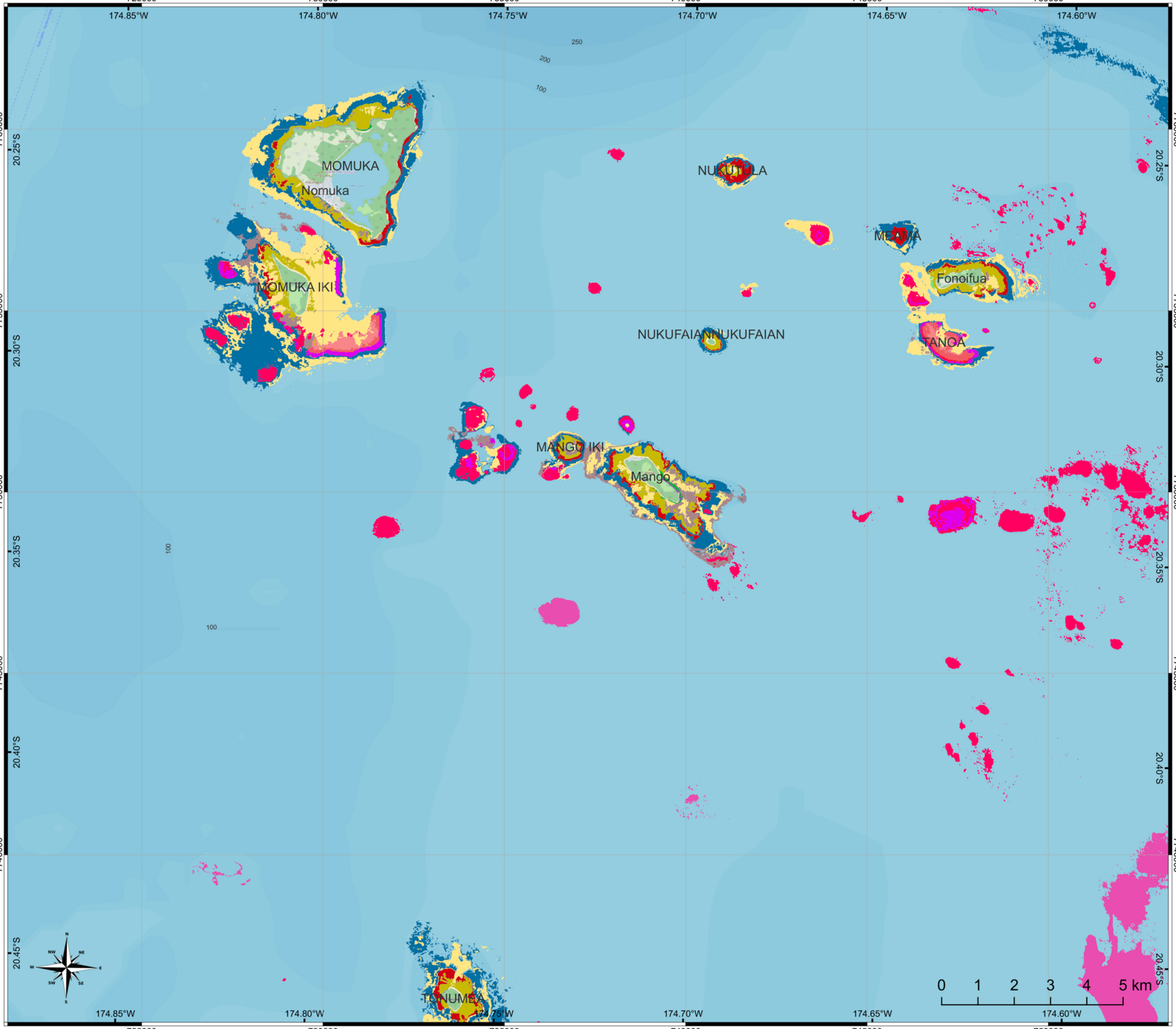
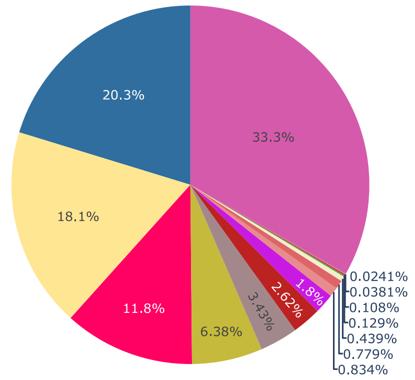


TABLE 17 OF 25 - T17

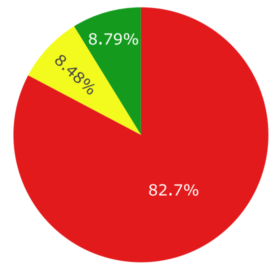
SCALE 1:100,000

MARINE HABITATS

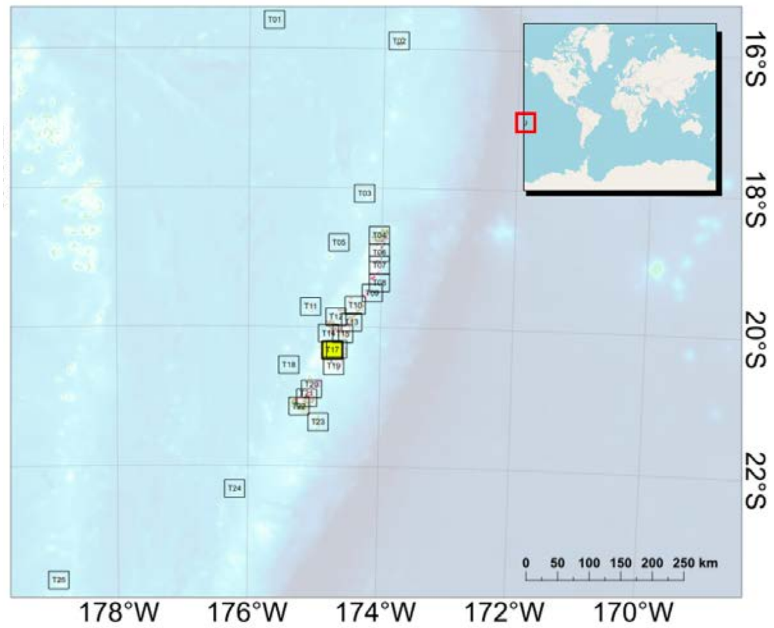


- Beach rock
- Back reef zone 1
- Back reef zone 2
- Back reef zone 3
- Fore reef
- Fringing reef
- Patch reef
- Reef bank
- Reef crest
- Reef flat
- Littoral sand
- Sand
- Seagrasses - High Density
- Seagrasses - Low Density
- Sparse coral

ECOLOGICAL QUALITY INDEX



- LOW
- MEDIUM
- HIGH



Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remore Sensing Image: Sentinel-2 (years 2018-2019)

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MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

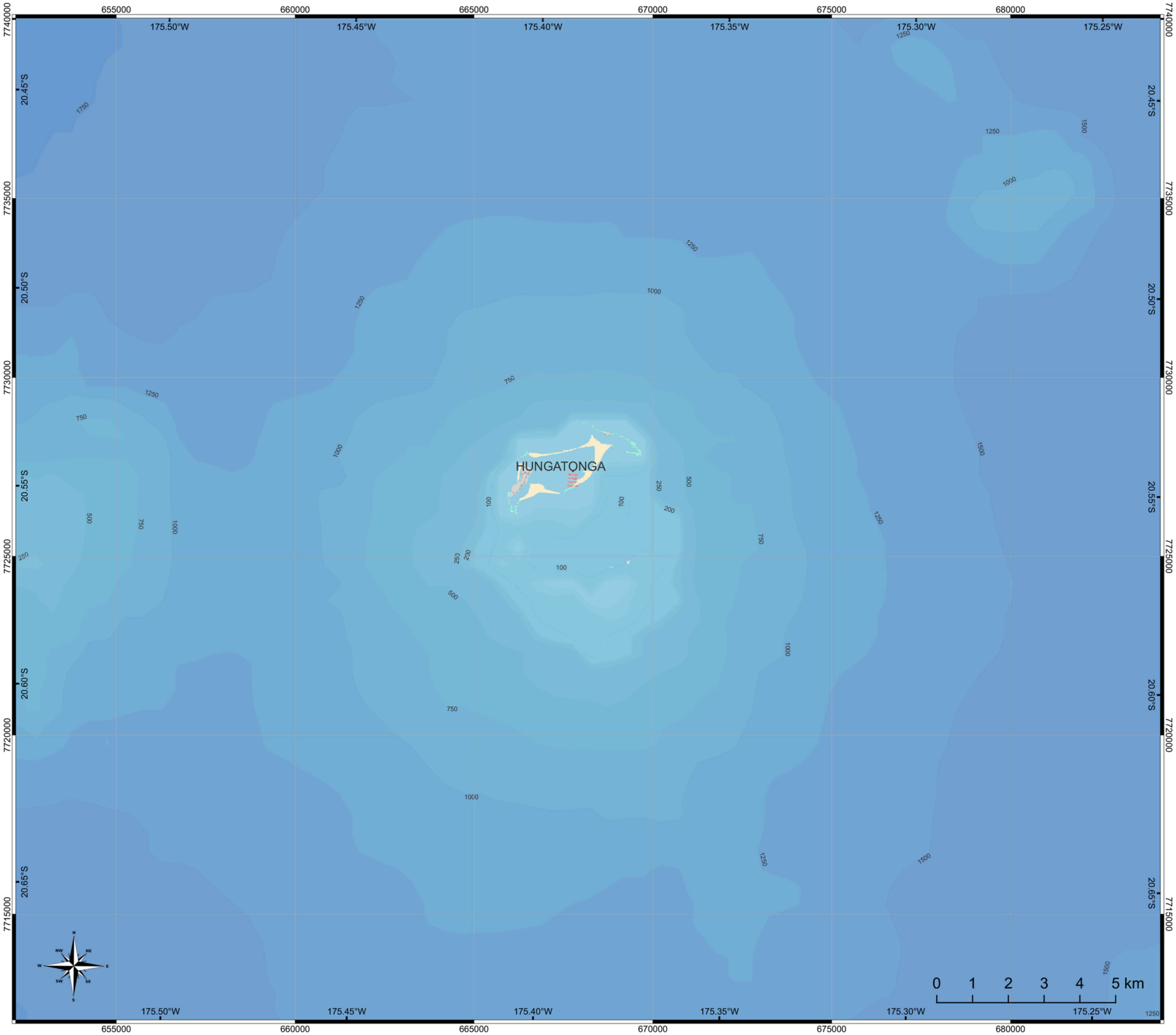
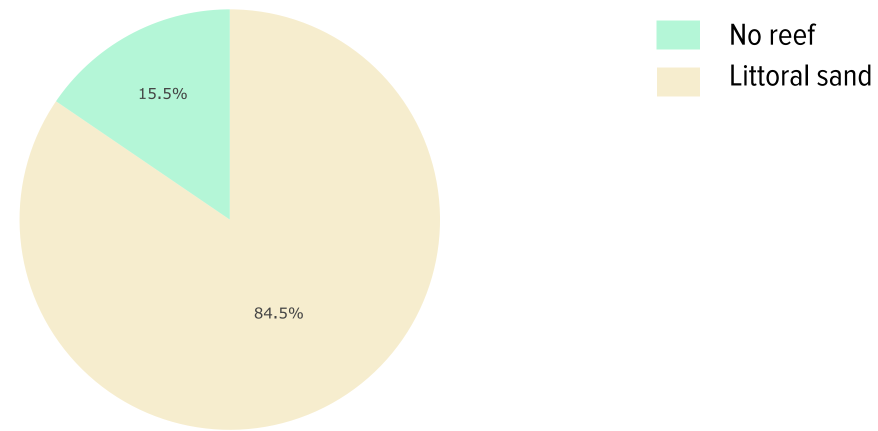
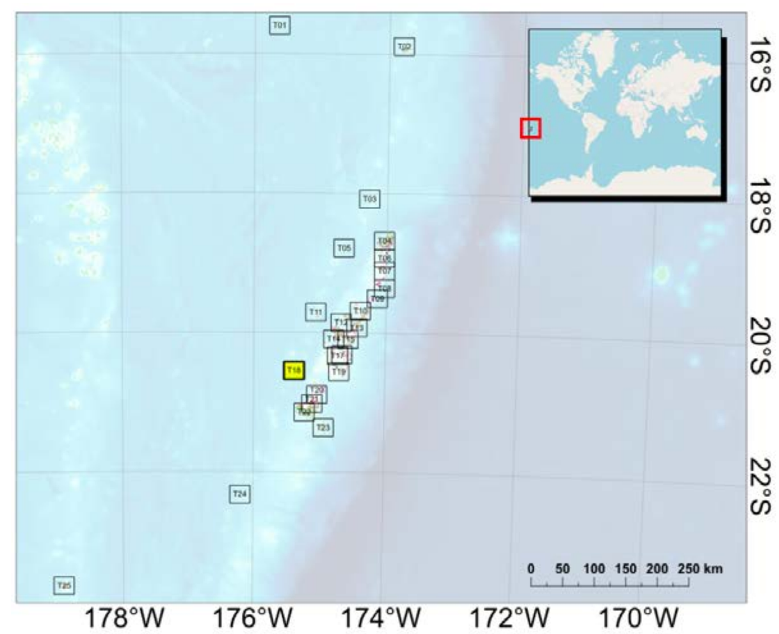


TABLE 18 OF 25 - T18

SCALE 1:100,000

MARINE HABITATS





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

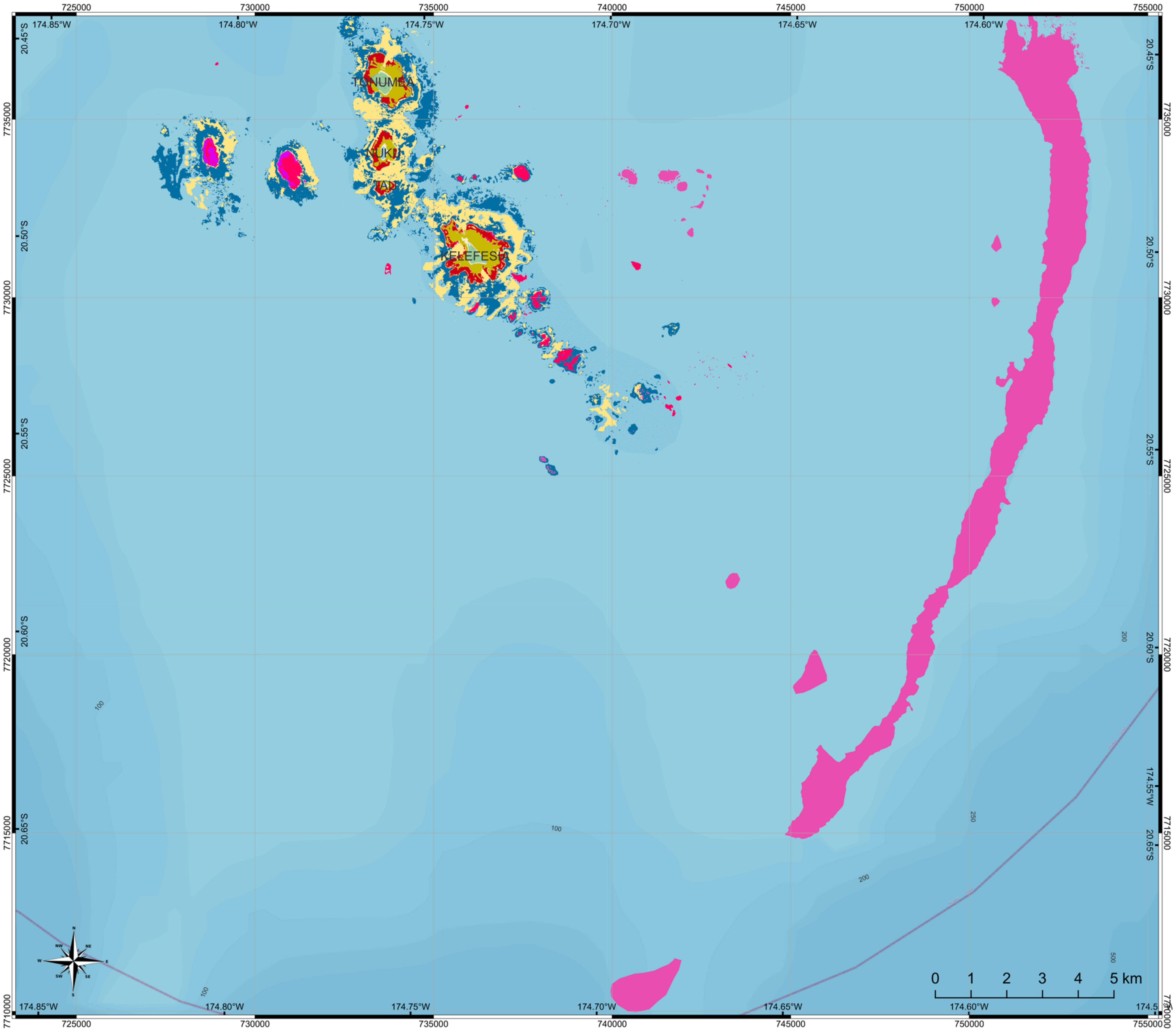
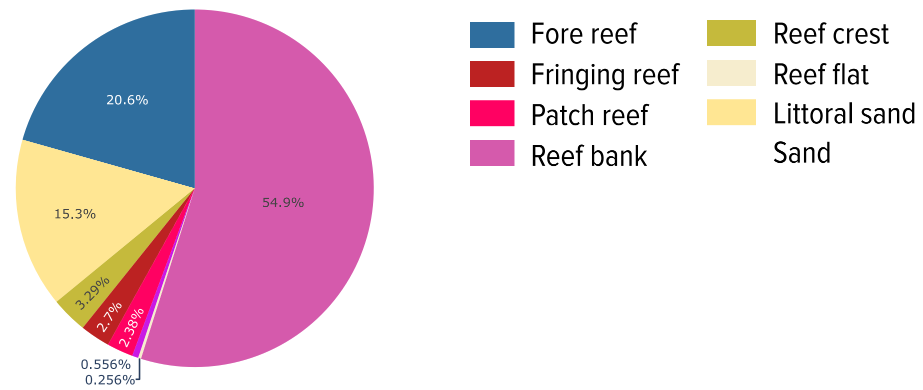


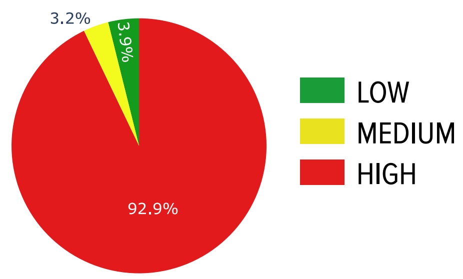
TABLE 19 OF 25 - T19

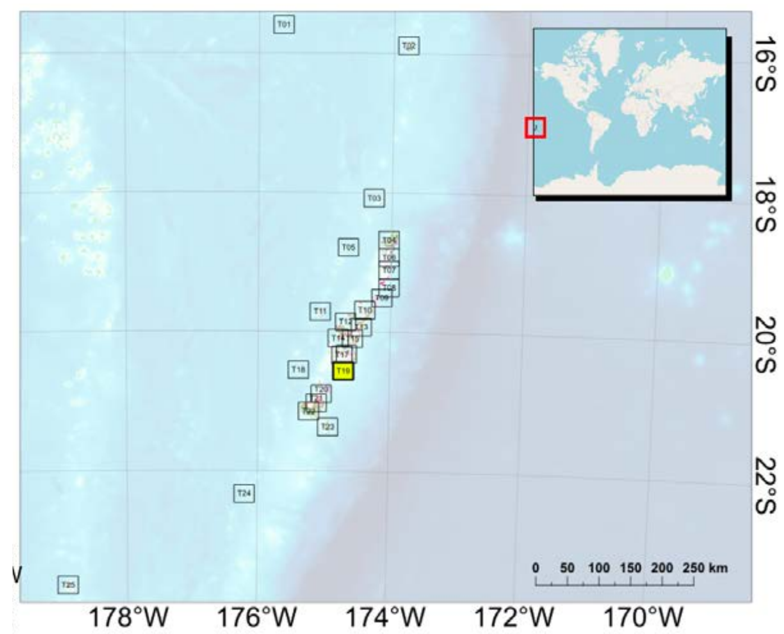
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

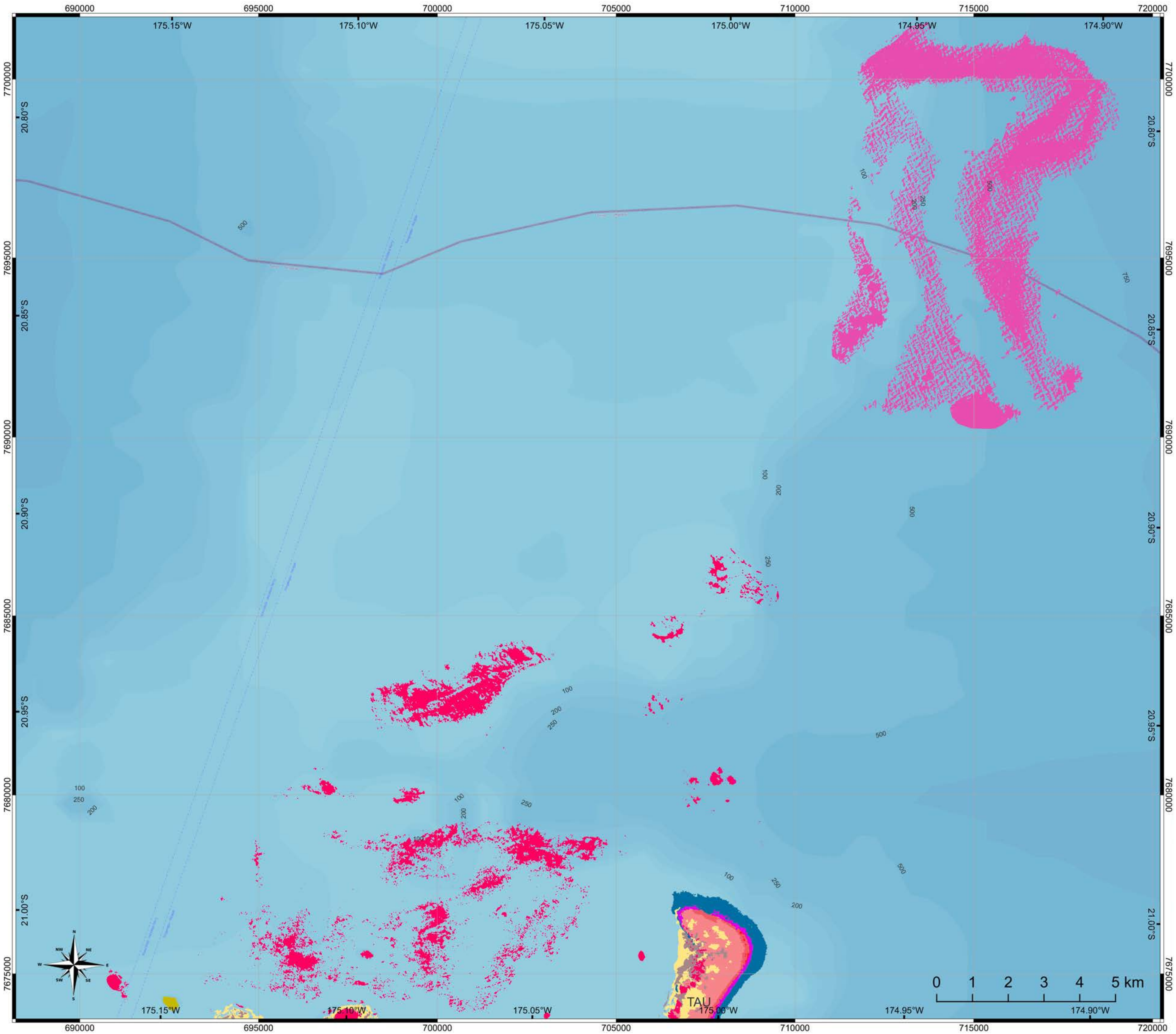
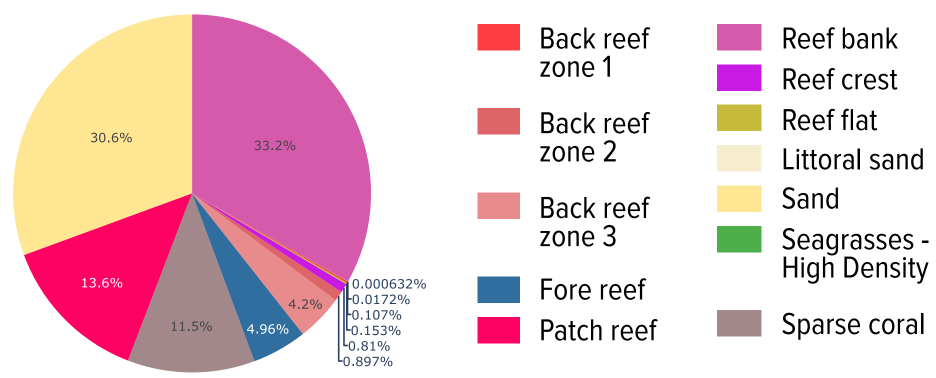


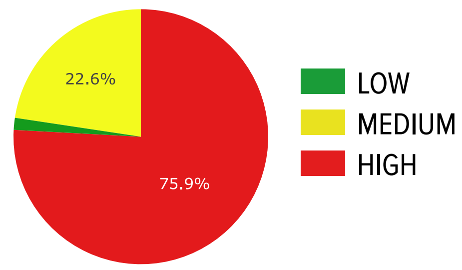
TABLE 20 OF 25 - T20

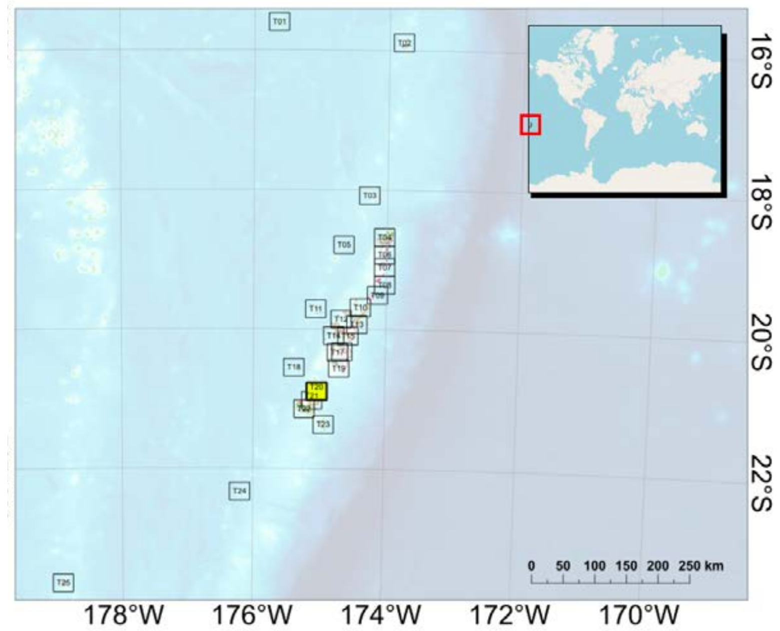
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

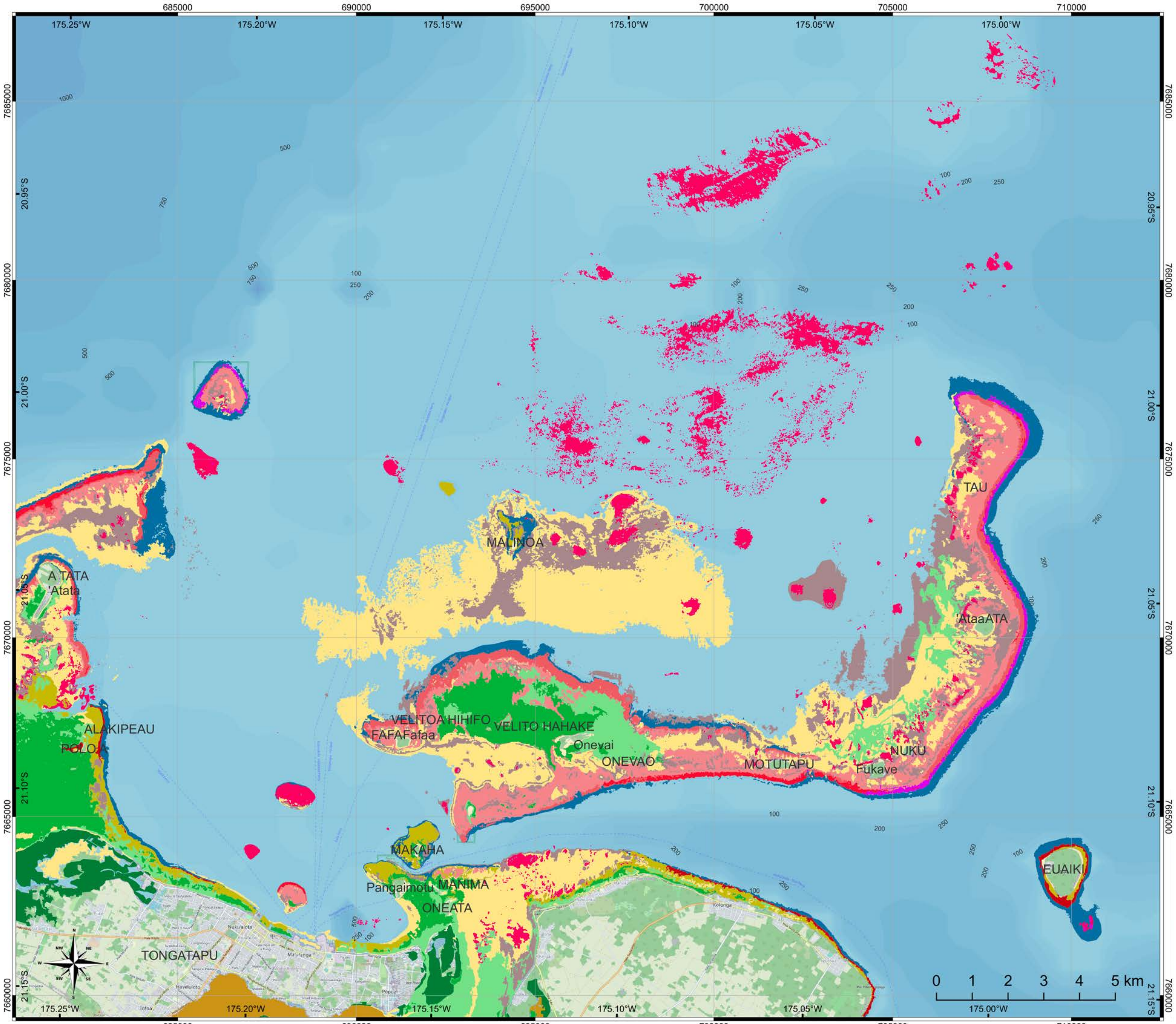
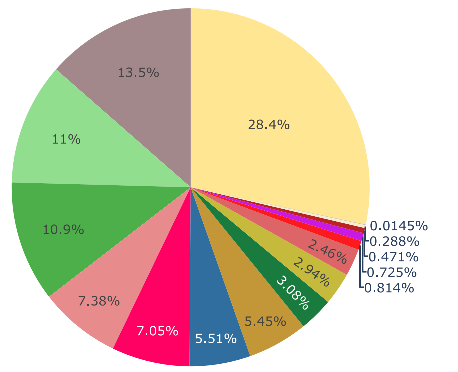


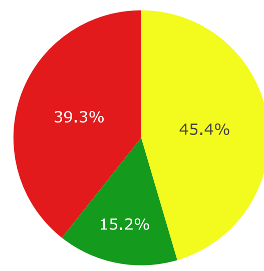
TABLE 21 OF 25 - T21

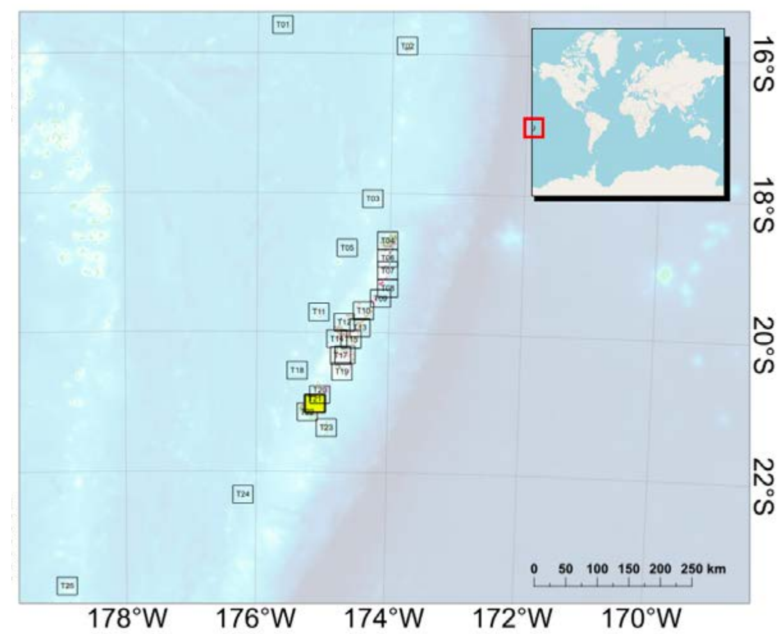
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

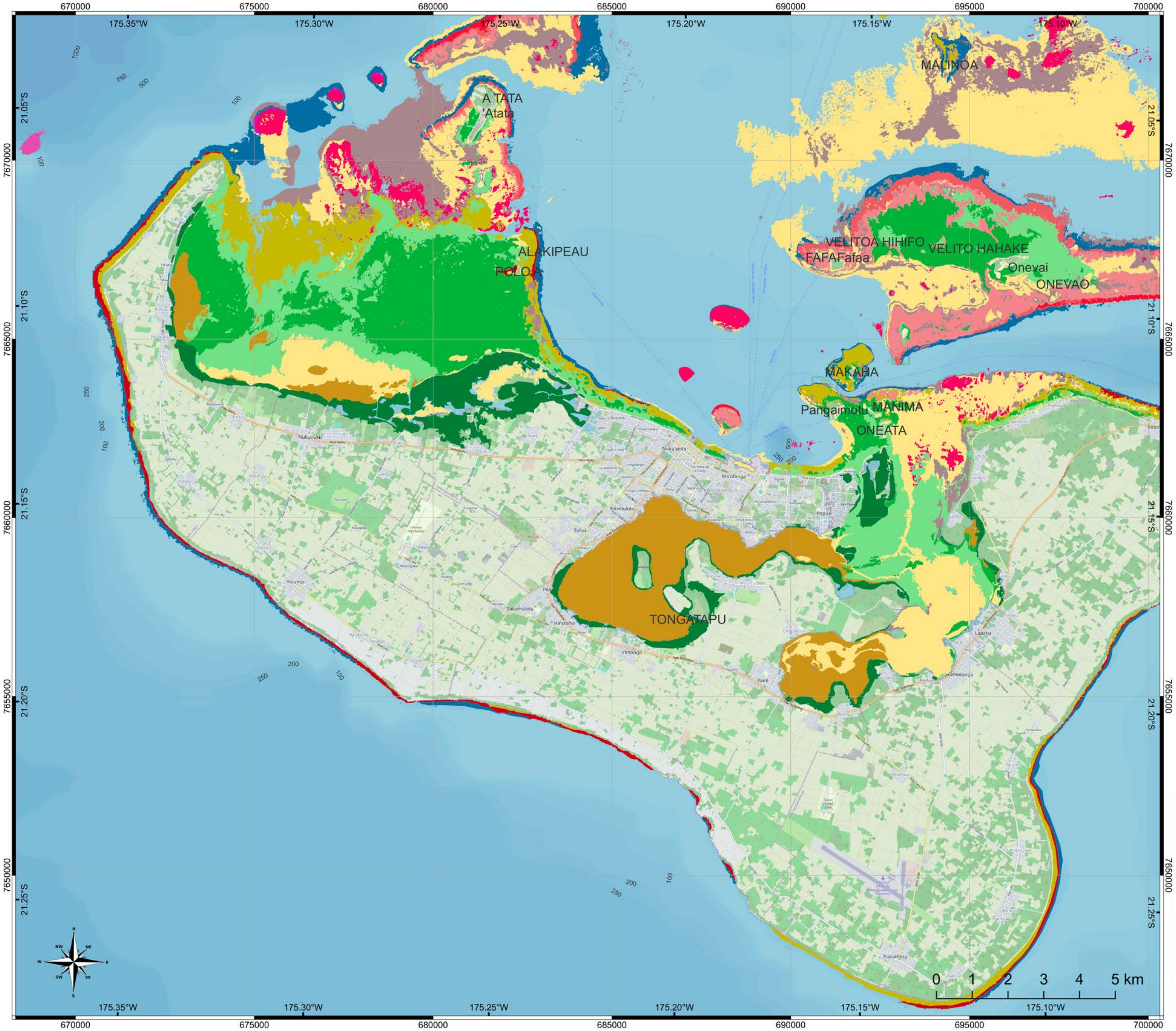
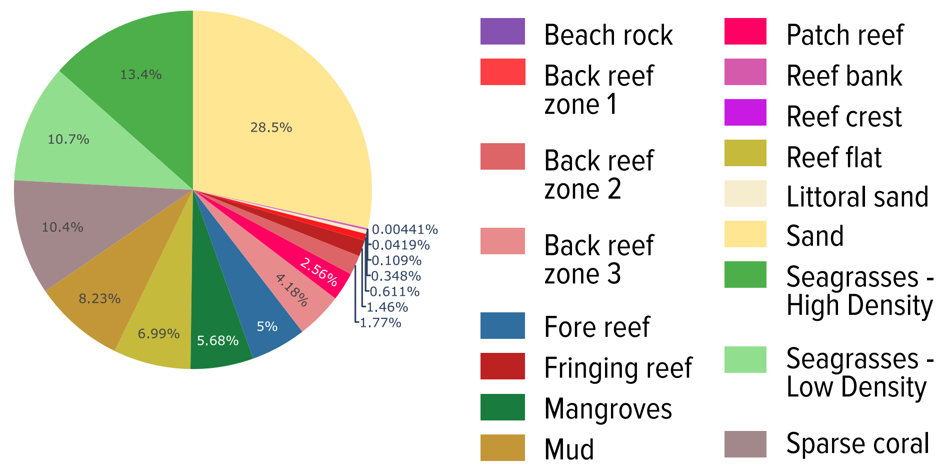


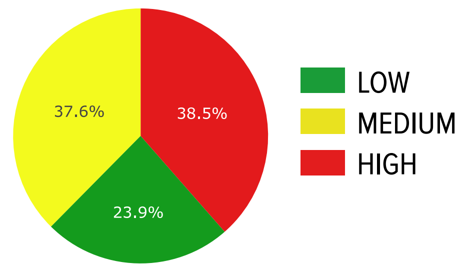
TABLE 22 OF 25 - T22

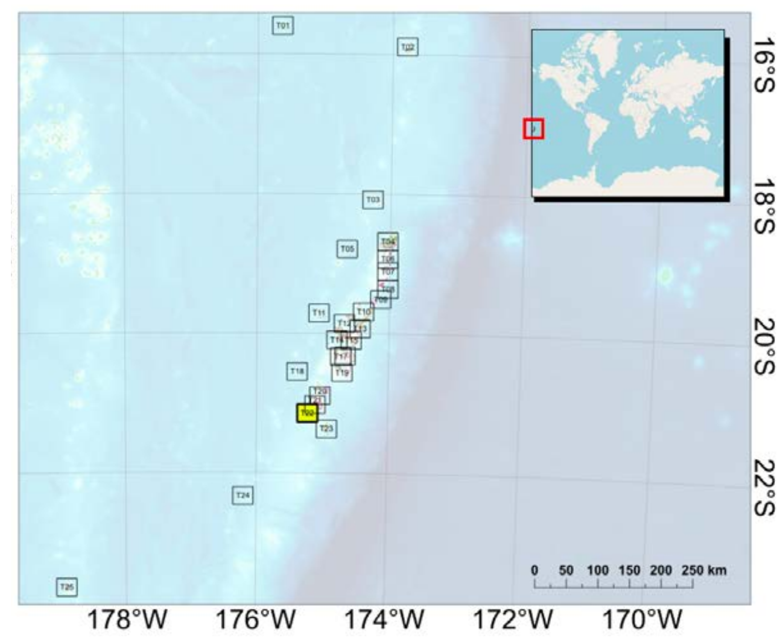
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

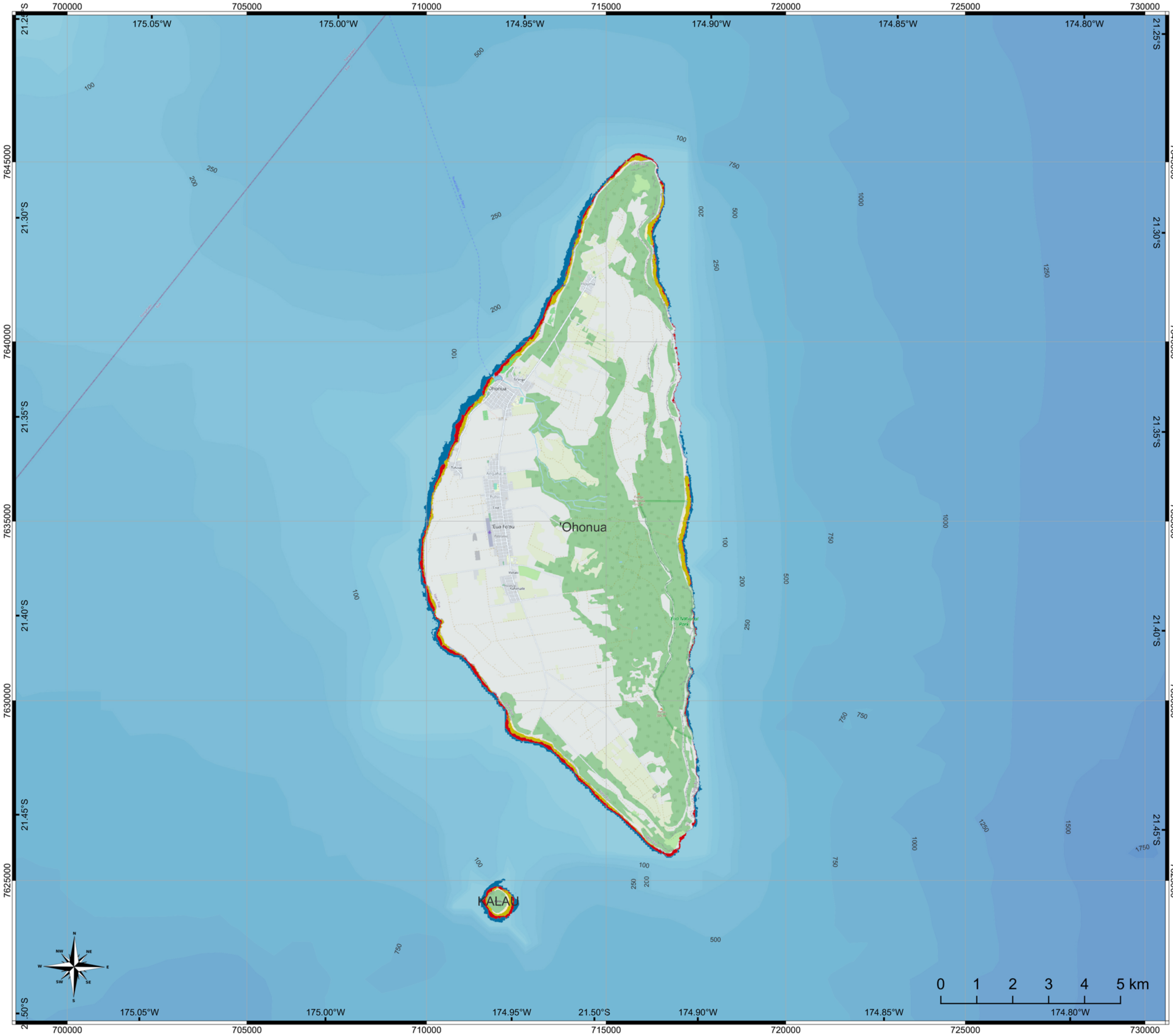
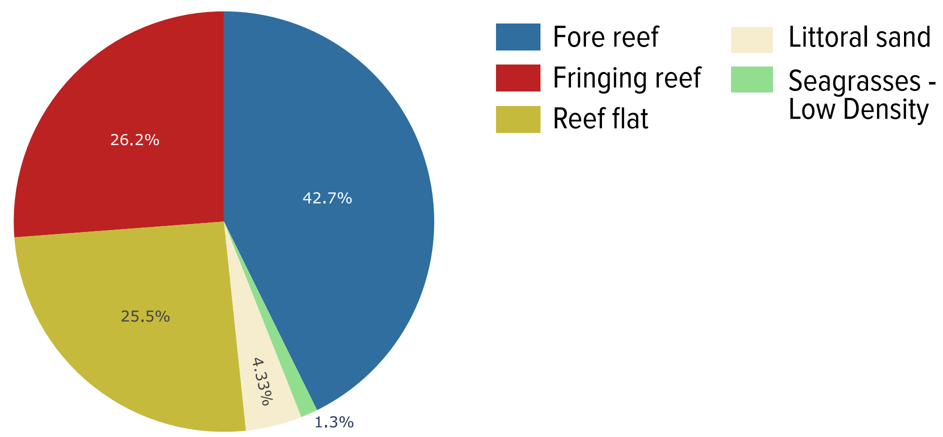


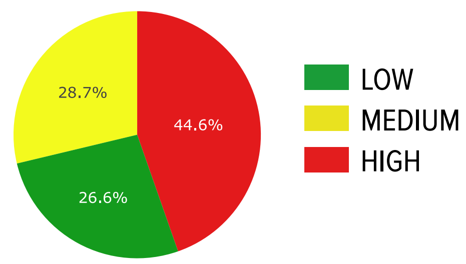
TABLE 23 OF 25 - T23

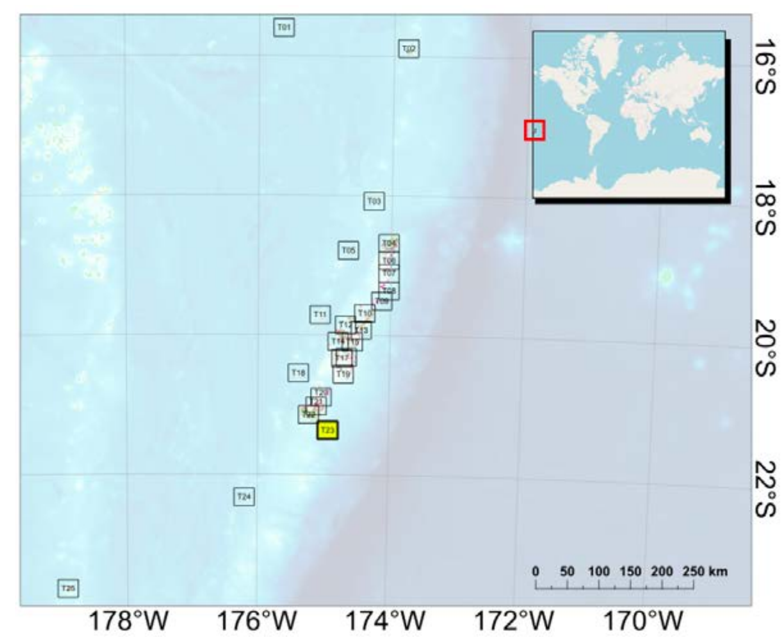
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

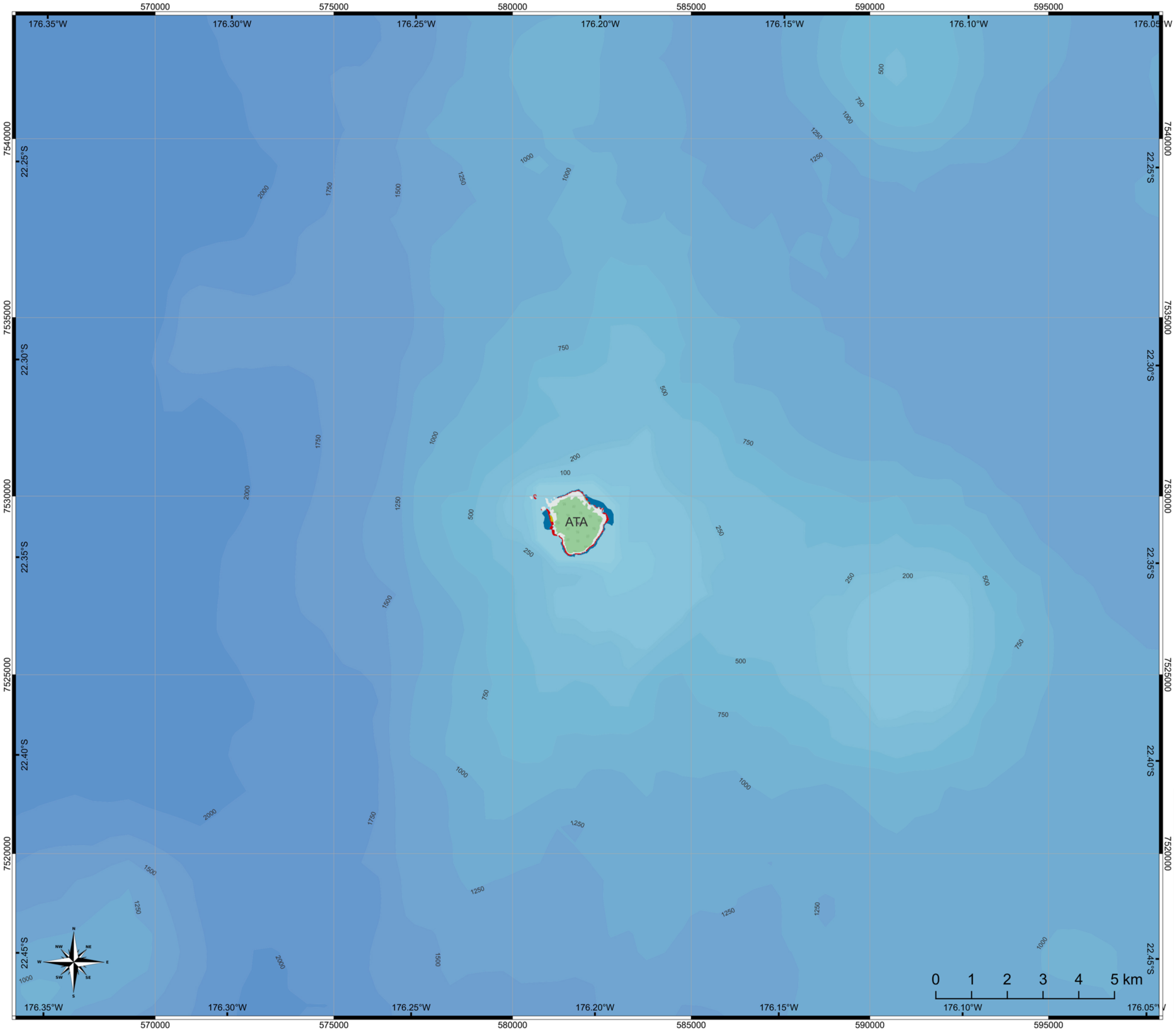
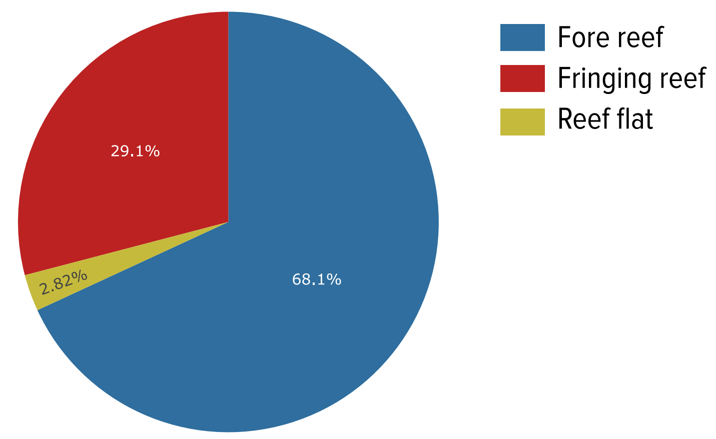
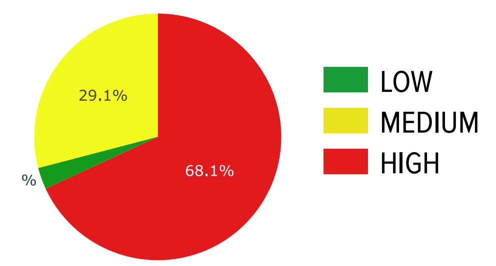


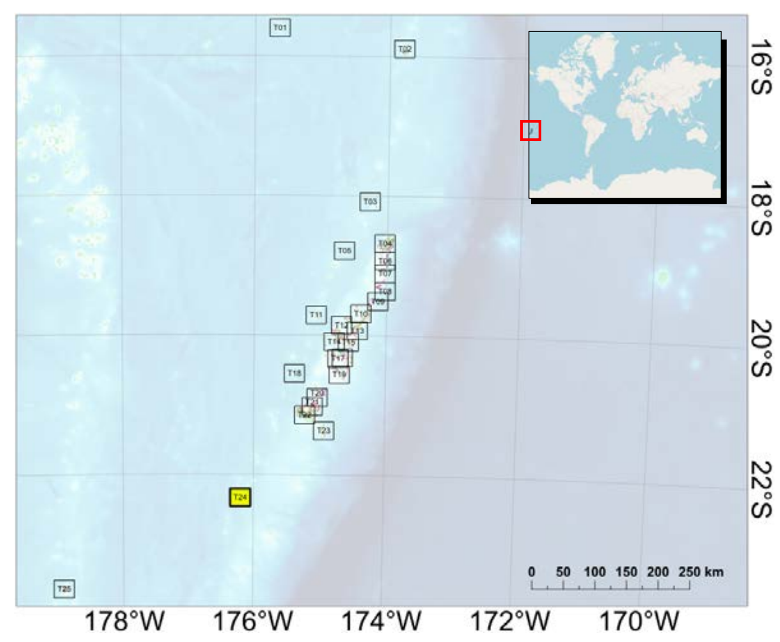
TABLE 24 OF 25 - T24
SCALE 1:100,000

MARINE HABITATS



ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)

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MINISTERO DELL'AMBIENTE E DELLA SICUREZZA ENERGETICA

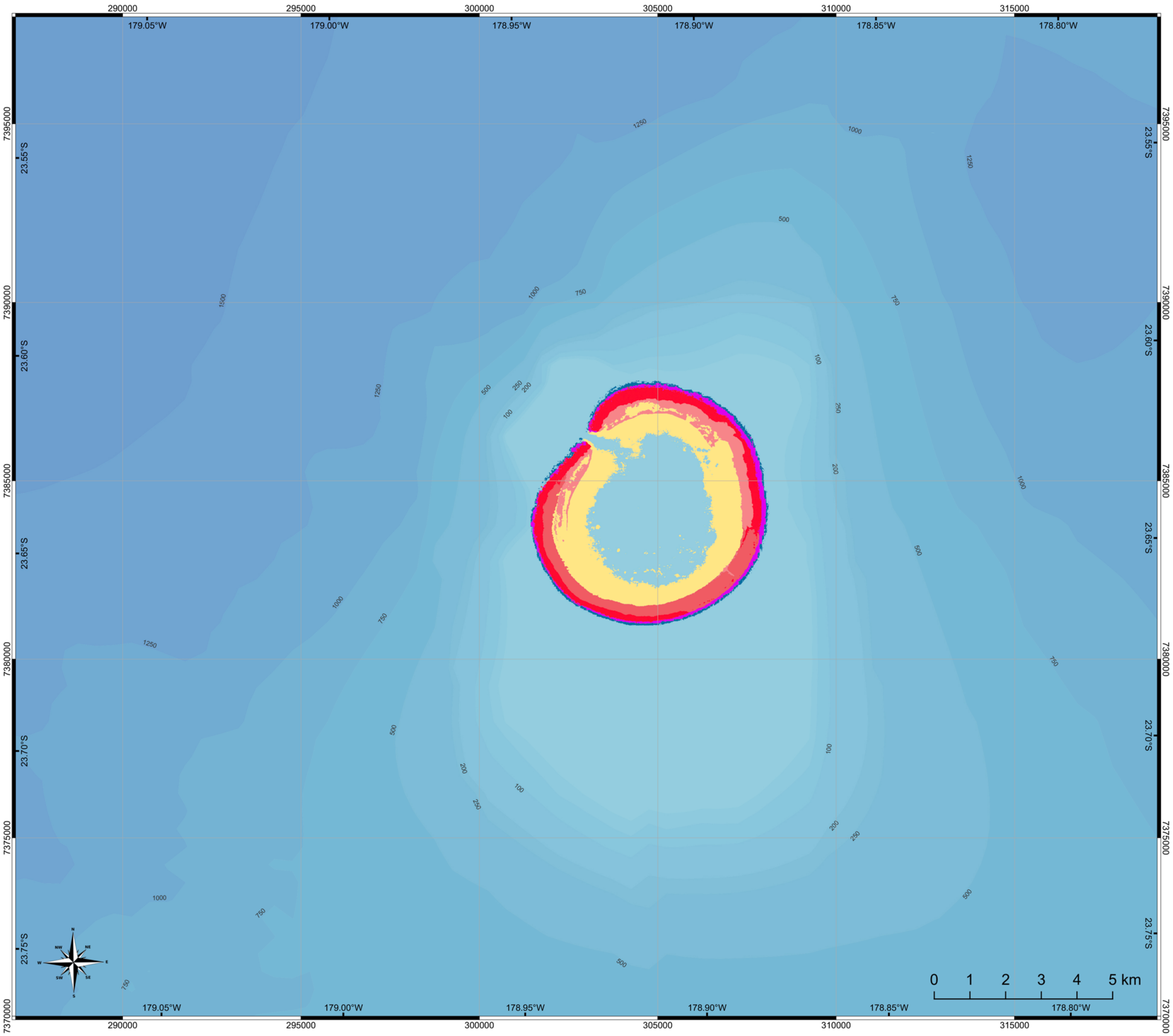
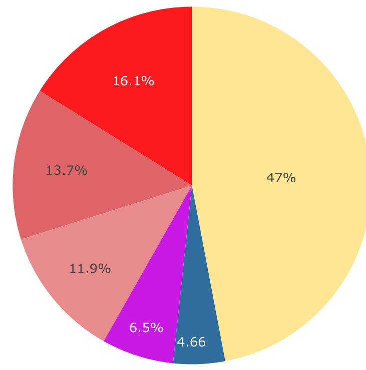


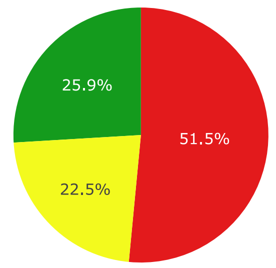
TABLE 25 OF 25 - T25

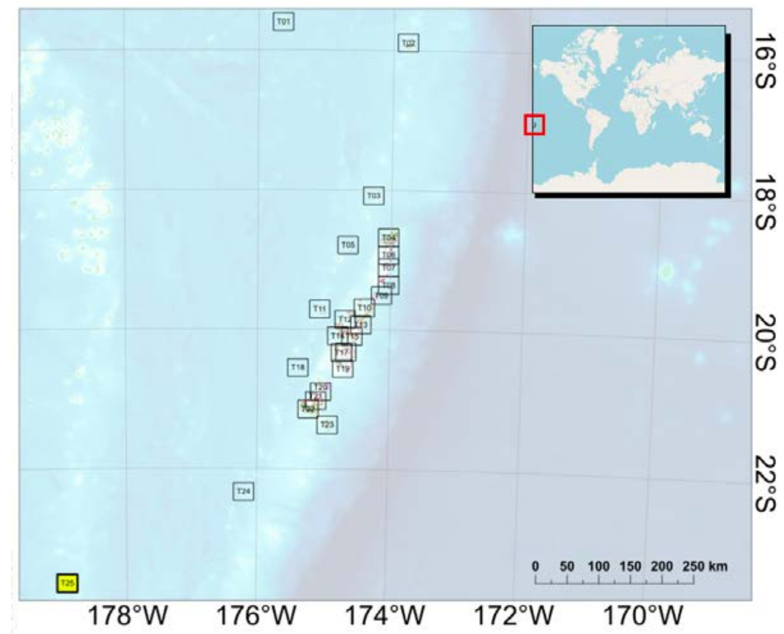
SCALE 1:100,000

MARINE HABITATS

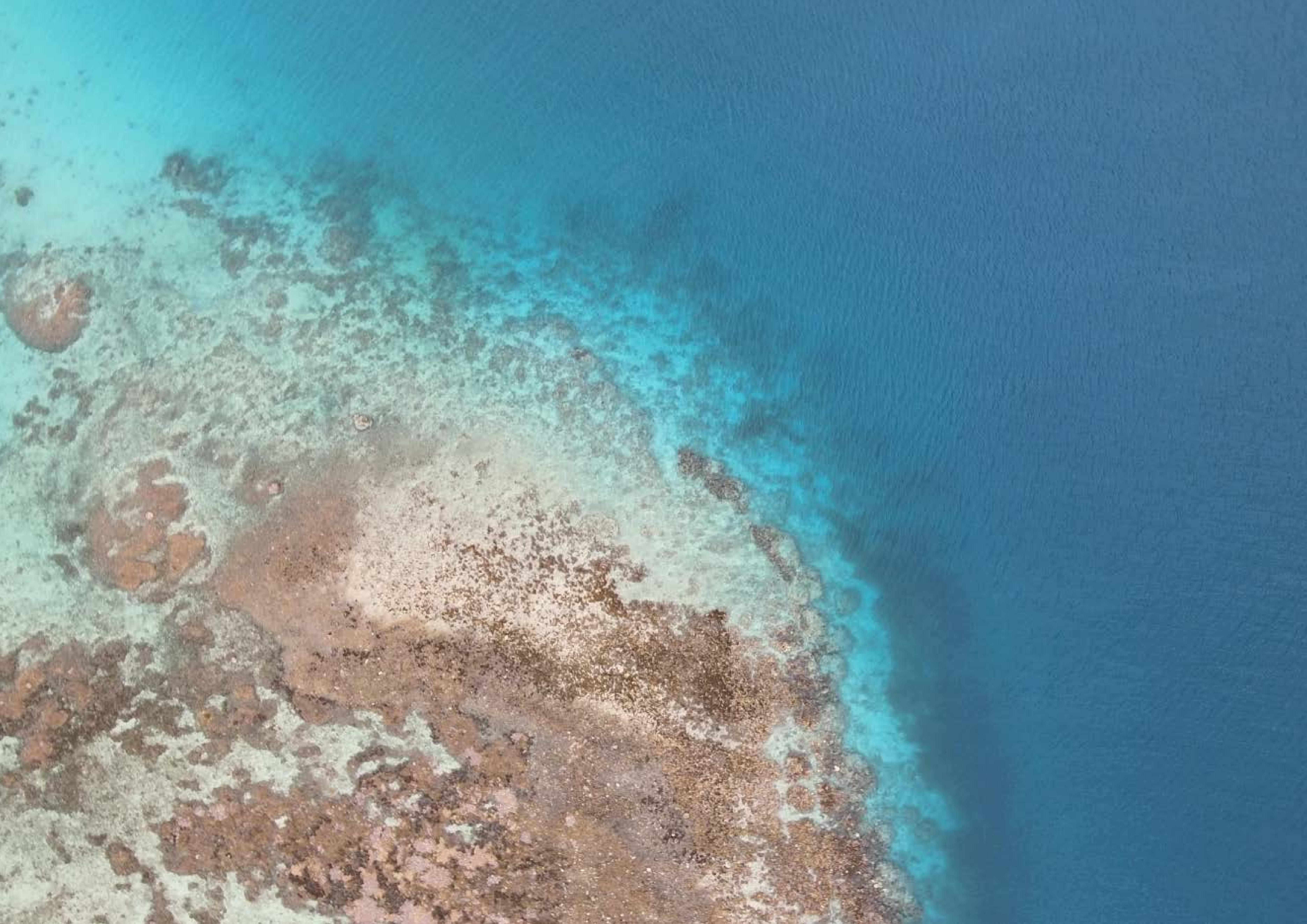


ECOLOGICAL QUALITY INDEX





Projected Coordinate system: WGS84 UTM Zone 1S - EPSG:32701
Geographic Coordinate system: WGS84 - EPSG:4326
Basemap: OpenStreetMap from OSM Foundation (year 2022)
Bathymetry: GEBCO General Bathymetric Chart of the Oceans (year 2021)
Remote Sensing Image: Sentinel-2 (years 2018-2019)



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KINGDOM OF TONGA

MINISTERO DELL'AMBIENTE
E DELLA SICUREZZA ENERGETICA

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES,
ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

TONGA METEOROLOGICAL SERVICE
Ministry of Meteorology, Energy, Information, Disaster Management,
Environment, Communications and Climate Change (MEIDECC)
KINGDOM OF TONGA
Official Government Website: Providing meteorological and maritime radio services in support of economic development,
safety and security and the general well-being of citizens and visitors to the Kingdom of Tonga.