Using satellite imagery to create a coastal habitat classification for use in conservation planning for the Three Kings Islands

Roderick James Lockie

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Supervisor: Dr Barbara Breen

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List of Acronyms

NZCP: The New Zealand Coastal Policy

MfE: Ministry for the Environment (MfE)

MPA: Marine Protected Areas

GIS: Geographic Information Systems

NIR: Near Infra-Red

ROI: Region Of Interests

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 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: ________________

Roderick James Lockie

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Abstract

There are fourteen coastal biogeographic regions that are used in conservation and management in New Zealand, with some that are remote and difficult to study the habitats within them. In the mapping of these remote regions, satellite imagery can assist in the process of creating a reserve network through the classification of marine and coastal habitats. The research created a coastal and nearshore marine habitat classification of the Three Kings Islands using the eight multi-spectral bands of the *WorldView-2* satellite imagery. This was done through the use of remote sensing and GIS software that helped in the identification and mapping of habitats. The habitats were then used in conjunction with *Marxan,* a decision support tool, to identify reserve systems that met the needs for biodiversity protection within the Three Kings Islands coastal biogeographic region. The Three Kings Islands coastal habitats have been identified through the use of satellite imagery with habitats identified within the terrestrial and marine zones. The habitats that were derived from the region of interests were more likely to be identified when using the classification results of maximum likelihood with all the bands available from the *WorldView-2* satellite. Using *Marxan* and the classified habitats from satellite imagery I have identified that using a scenario of 30% could be used in any conservation strategy that is employed by the management authority of the biogeographic region as it selected the largest areas of irreplaceability.

Introduction

1.1 Coastal environments, their conservation and management

Coastal environments

Coastal environments make up 20% of the earth's surface, holding a diverse range of habitats that cater for a wide variety of terrestrial and marine species (Duarte, Dennison, Orth, & Carruthers, 2008; Martínez et al., 2007). Coastal biodiversity is increasingly at threat from human led impacts around the world (Duarte et al., 2008). This is one reason why the conservation and management of these environments is essential to protect for future generations (Duarte et al., 2008; Martínez et al., 2007).

As an island nation, New Zealand has a coastline that is up to 18,000 km in length and home to a variety of indigenous species in marine and terrestrial ecosystems (Goldstien et al., 2010; Hart & Bryan, 2008). The New Zealand Coastal Policy (NZCP) was created in 1994 and updated in 2010 as part of an effort to protect and promote sustainable management of New Zealand coastal environments (Department of Conservation, 2010; Hart & Bryan, 2008). The NZCP outlines ways to protect ecosystems and habitats, including marine and intertidal areas, estuaries, dunes and land (Department of Conservation, 2010). The NZCP coexists with the Ministry for the Environment (MfE) coastal management tools that have been created to help in the classification of important regions around New Zealand (Ministry for the Environment, 2011a).

Conservation and management

The MfE created a classification system as an important tool in the classification and mapping of a variety of habitats from land, freshwater and marine ecosystems around New Zealand (Ministry for the Environment, 2011a). With the help of these classification guidelines, agencies can use available environmental data to help in the management of ecologically similar regions (Ministry for the Environment, 2011a). The MfE created a broad scale land cover database classification of terrestrial habitats that identified nine major classes using satellite imagery between 1996/97 and 2001/02 02 (Ashraf, Brabyn, Hicks, & Collier, 2010; Ministry for the Environment, 2011b). Comparatively, the marine classification system has led to the creation of fourteen coastal biogeographic regions that encompass areas around the New Zealand coast down to a depth of 200 m (Figure 1) (Department of Conservation & Ministry of Fisheries, 2008; Ministry for the Environment, 2011c).

These biogeographic regions have been defined into areas that cover obvious patterns in the ecology and physical characteristics that make up the geography or hydrography of an area (Ministry for the Environment, 2011c). It is an approach that takes into account the distance between the biogeographic regions and the likelihood that they will comprise distinct biological communities due to a combination of broad-scale factors (Department of Conservation & Ministry of Fisheries, 2008).

From the broad-scale factors, the classifications of these biogeographic regions are then split into the either estuarine or marine environments which are used to recognise the fundamental differences in organisms associated in the estuarine and marine environments. These environments are further separated into factors that influence the site biology. These factors are depth, exposure and substrate type (Table 1). Altogether, there are forty four potential marine habitats within the 14 coastal biogeographic region; however not every biogeographic regions will contain all these habitats (Department of Conservation & Ministry of Fisheries, 2008).

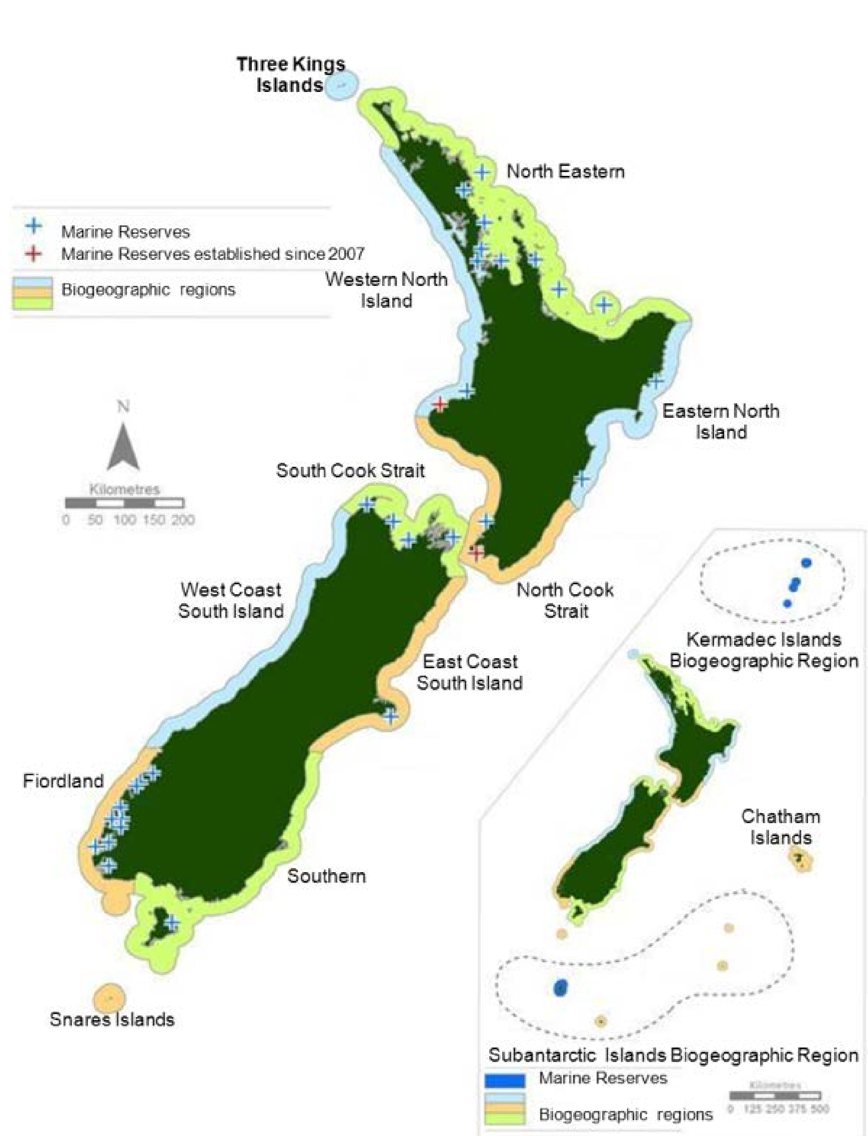

Figure 1. The fourteen biogeographic regions of New Zealand (MfE, 2008)

These classification methods using the habitats identified using Table 1, can help in monitoring the state of the environment within coastal biogeographic regions and be used in the processes of conservation and management such as the implementation of marine protected areas (MPAs) (Department of Conservation & Ministry of Fisheries, 2008; Ministry for the Environment, 2008).

Table 1. Coastal classification and mapping scheme (MHWS - 200 metre depth) (Department of Conservation & Ministry of Fisheries, 2008)

Level 1	Biogeographic region (14)									
Level 2	Environment type	Estuarine		Marine						
Level 3	Depth	Intertidal	Subtidal	Intertidal (MHWS– MLWS)			Shallow Subtidal (MLWS – 30 m)			Deep Subtidal (30 m – 200 m)
Level 4	Exposure	Low	low	low	med	high	low	med	high	low
Level 5	Habitat type	Mud flat Sand beach Gravel beach Cobble beach Boulder beach Rocky platform	Mud flat Sand flat Gravel field Cobble field Boulder reef Rocky reef Biogenic reef	Mud flat	Sandy beach Gravel beach Boulder beach Rocky platform	Sandy beach Gravel beach Boulder beach Rocky platform	Shallow mud	Shallow sand Shallow gravel field Shallow cobble field Shallow boulder reef Shallow biogenic reef	Shallow sand Shallow gravel field Shallow cobble field Shallow boulder reef Shallow biogenic reef	Deep mud Deep sand Deep gravel field Deep cobble field Deep boulder field Deep rocky reef Deep biogenic reef

Marine Protected Areas

Dividing each coastal biogeographic region into the four levels of environment type, depth, exposure and habitat, provides a way to classify the regions in a consistent manner (Department of Conservation & Ministry of Fisheries, 2008; Snelder et al., 2005). This is then able to meet the demands of a variety of applications, of which the management and protection of marine habitats is an important aspect (Department of Conservation & Ministry of Fisheries, 2008; Ministry for the Environment, 2008; Snelder et al., 2005).

This classification method was developed after the New Zealand government adopted the goals and criteria for the development of a nationally representative system of MPAs (ANZECC/TFMPA, 1998). This resulted in the development of the MPA policy which came about from the New Zealand Biodiversity Strategy, both of which have a goal to "*Protect marine biodiversity by establishing a network of MPAs that is comprehensive and representative of New Zealand's marine habitats and ecosystems.*" (Department of Conservation & Ministry of Fisheries, 2005; New Zealand Biodiversity, 2000). The MPA policy defines an MPA as "*An area of the marine environment especially dedicated to, or achieving, through adequate protection, the maintenance and/or recovery of biological diversity at the habitat and ecosystem level in a healthy functioning state.*" (Department of Conservation & Ministry of Fisheries, 2005).

This is where classifications within a coastal biogeographic region come into the implementation of creating a MPA network which covers a range of habitats and ecosystems. These MPA networks use the levels outlined in Table 1 to cover a representative range of habitats within a biogeographic region (Department of Conservation & Ministry of Fisheries, 2008; Stevens, 2002).

In the New Zealand MPA policy, there are two main types of management tools that are used to create MPA's; this includes marine reserves, other MPAs and marine protection tools. The most protection exists in marine reserves where there are limits on a broad range of activities for the purpose of protecting marine life (Department of Conservation & Ministry of Fisheries, 2005, 2008). A marine reserve can be established through the use of Marine Reserves Act 1971, and has the purpose of preserving marine life for scientific study. This allows for the management of activities within the limits of the reserve. This often involves the controlled use or exclusion of fishing, marine farming, anchoring, research and tourism (Department of Conservation & Ministry of Fisheries, 2005, 2008).

Other MPAs exercise prohibitions on fishing by the Fisheries Act 1996 for the purpose of sustaining fisheries resources (Department of Conservation & Ministry of Fisheries, 2005, 2008). This can include limiting fishing techniques within certain areas as well as protecting manmade obstructions. These can also be protected by acts such as the Crown Minerals Act 1991, Maritime Transport Act 1994 or the Biosecurity Act 1993 (Department of Conservation & Ministry of Fisheries, 2005, 2008).

Local fisheries related to cultural significance with Maori can also be protected through Taiapure or Mataitai. These are local management tools that provides fishing on grounds that have customary significance to an iwi or hapu (Ministry of Fisheries, 2007a, 2007b). The difference between the two refers to the ability to undergo commercial fishing. Where Taiapure allows commercial fishing ventures, however, places limits on the type and quantity of catch, along with restrictions on the fishing technique employed (Ministry of Fisheries, 2007b). Mataitai on the other hand, stops all commercial fishing within the area while still allowing recreational use (Ministry of Fisheries, 2007a).

The majority of these MPAs require knowledge of the area before any plan can be put in place to protect them. The MPA Classification, Protection Standard and Implementation Guidelines are used by managers to identify areas of importance (Department of Conservation & Ministry of Fisheries, 2008; V. Kerr, 2009). These guidelines use the identified coastal biogeographic regions by MfE to help in the planning process (Department of Conservation & Ministry of Fisheries, 2008). Once classification of habitats has been done within a coastal biogeographic region it goes through three guidelines to identify potential MPAs (Department of Conservation & Ministry of Fisheries, 2005):

- Site identification and protected area design guidelines: This provides the foundation for identifying sites that could be used in a MPA.
- Site selection guidelines: This uses the identified sites from above and recommends one for protection.
- Tool selection guidelines: This recommends what protection status the site will get from the possible types of MPAs that can be used.

From these guidelines, a final MPA will be created that is representative, of international or national importance, or fills in network gap and priority habitat and ecosystems of a biogeographic region (Department of Conservation & Ministry of Fisheries, 2008). This is relevant to remote biogeographic regions where it is difficult to get a full assessment of the coastal habitats within them. In the mapping of these remote regions, satellite imagery can assist in the process of creating a MPA network through the classification of marine and coastal habitats.

1.2 Satellite remote sensing of coastal environments

Habitat classification of coastal environments

The use of satellite imagery in remote sensing has been documented since the first earth observation satellite was launched in the early 1970s (Hamilton, 1977; Morain, 1998). This was the launch of the first *Landsat* satellite in 1972 which has now become ubiquitous with remote sensing satellites (Hamilton, 1977; Klemas, 2011; Morain, 1998; P. J. Mumby, Green, Edwards, & Clark, 1997). The creation of the *Landsat* range of satellites in the 1970s was due to the demand for a better understanding of earth's landscapes, national security, commercial opportunities, international cooperation and international law (Armstrong, J, & D, 2005; Morain, 1998). Since *Landsat's* inception, it has helped scientists study and map the earth's surface, from the use in predicting forest fires, classifying habitats for conservation, land-use in urban or rural settings, geology, mapping, coastal and marine habitats (Daus & Cosentino, 1977; Oswald, 1976; Smith, Rogers, & Reed, 1975).

Satellite imagery in coastal environments started with the use of *Landsat* by Smith, Rogers, & Reed (1975) when they used imagery to map a reef system in a remote location on the Great Barrier Reef. This was followed by Jupp, Mayo, Kuchler, Claasen, Kenchington, & Guerin (1985) who showed that remote sensing could be used in the planning and management of large marine systems such as the Great Barrier Reef. From these studies, other habitats have been identified through the use of *Landsat* imagery. For example, Lennon & Luck (1989) used the *Landsat TM* to identify seagrass communities using the spectral bands available to distinguish between submerged and exposed seagrass beds.

The studies of the Great Barrier Reef have been followed by more recent studies with the use of more advanced imaging satellites in other tropical reefs around the world. This includes a study by Mumby & Edwards (2002) on the use of *IKONOS* imagery (4 m spectral resolution) to classify habitats around the Turks and Caicos Islands in the British West Indies. It compared the use of the high resolution satellite *IKONOS* to the *Landsat TM* in mapping marine coral reefs and seagrass communities and found that the higher resolutions improved classification results.

The classification of habitats has been enhanced with the newer high resolution images as seen in Fonseca, Soto, Cortés, & Guzmán (2010) by the use of *Quickbird* images (2 m spectral resolution) as compared to *Hymap* images (16 m resolution).

Satellite remote sensing has also been used in the mapping of seaweed communities that cover small regions as seen in unpublished work done for DigitalGlobe's 8 Band Challenge for the *WorldView-2* (Agustan, Frederik, Andiastuti, & Hendiarti, 2011; DigitalGlobe, 2011). *WorldView-2* was also used in the mapping of kelps forests on the European Atlantic shelf by Casal, Sánchez-Carnero, Sánchez-Rodríguez, & Freire (2011) who found that they could map kelp habitats with up to 70% accurately.

Satellite remote sensing in New Zealand

New Zealand has been using satellite imagery in remote sensing since the first images were available from *Landsat* in the 1970s. Cochrane & Male (1977) used *Landsat* imagery to map the regional and seasonal sediment discharges along the New Zealand coast. Other research done prior to 1990 has been on land cover classifications using *Landsat* and multispectral aircraft scanners and in measuring sea surface temperatures and chlorophyll levels in New Zealand waters (Belliss, 1984).

In the New Zealand coastal zone satellite imagery has been used to test the sensitivity of *SPOT XS* imagery for monitoring in the Otago Harbour. Israel & Fyfe (1996) found it was possible to determine intertidal and sub-littoral vegetation and to monitor the health and distribution of eelgrass communities from *SPOT XS* imagery. Gao, Chen, Zhang, & Zha (2004) used *SPOT* imagery to classify and map mangrove forests within Auckland's Waitemata Harbour. They used a knowledge based approach to accurately map up to 83% of stunted and 96% of lush mangrove forests.

MfE has used satellite imagery that has focused on the creation of the land cover database in which mapping was done using *SPOT* satellite images from 1996/97 and more recently from *Landsat -7 ETM+* from 2001/02 (Ashraf et al., 2010; Thompson, Grüner, & Gapar, 2003). This land cover database was created to classify regions and help in the assessment of land cover for management purposes (Thompson et al., 2003).

Other studies in New Zealand have used satellite remote sensing to assess the changes of environment in natural landscapes. This includes studying the change in volcanic activity through *ASTER* satellite data by Joyce, Samsonov, and Jolly (2008). This study found it could accurately map lahar flows from Mt Ruapehu while also providing temperature fluctuations from within the Crater Lake. *ASTER* satellite data have also been used in mapping New Zealand glaciers in Mathieu, Chinn, and Fitzharris (2009) which looked at comparing its accuracy to aerial photography.

Ashraf et al. (2010) reviewed the use of satellite remote sensing in the mapping of vegetation within New Zealand freshwater environments. They identified the use of a variety of satellites that could have the potential to be used within New Zealand. However, they concluded that using high spatial and spectral resolution images fit better in assessing freshwater environments.

Satellite remote sensing for coastal applications

There are many different types of satellites being used today for coastal and marine applications; however the majority of them were designed with terrestrial environments in mind (Green, Mumby, Edwards, & Clark, 1996). This has not stopped a wide variety of studies using them for marine applications and with the increasing number of satellites being used to observe earth, there are some useful tools that are available. The satellites rely on the use of differing sensor imaging satellites to thermal infrared and radar satellites that are able to observe different parameters from the ocean surface or below (Table 2)(Brown, Connor, Lillibridge, Nalli, & Legeckis, 2005).

Table 2. List of parameters with observational category and example satellites (Brown et al., 2005)

Parameter	Observational Category	Example Satellite/Sensors
Bio-optical	Visible – Near Infrared	*WorldView-2, Quickbird*
Bathymetry	Visible – Near Infrared	*WorldView-2, Landsat, Spot*
Sea surface temperature	Thermal Infrared Microwave Radiometers	*POES/AVHRR* *GOES/Imager*
Sea surface salinity	Microwave Radiometers & Scatterometers	
Sea surface roughness, Wind velocities, Waves & tides	Microwave Scatterometers & Altimeters Synthetic Aperture Radar	*ERS-1 & -2/AMI* *QuickSCAT* *RADARSAT-1*
Sea surface height, Wind speeds	Altimeters	*Topex/Poseidon* *Jason-1*
Sea ice	Visible – Near Infrared Microwave Radiometers, Synthetic Aperture Radar	*POES/AVHRR* *ERS-1 & -2/AMI* *DMSP/SSM/I*
Surface currents, Fronts & Circulation	Visible – Near Infrared Thermal Infrared Microwave Radiometers, Scatterometers & Altimeters	*POES/AVHRR* *GOES/Imager Topex/Poseidon* *Jason-1*
Surface objects- Ships, Wakes & Flotsam	Synthetic Aperture Radar	*RADARSAT-1* *Envisat/ASAR*

The majority of studies rely on visible – near infrared satellites that can take colour imagery down to a resolution of 41 cm in the highest resolution sensors (Ünsalan & Boyer, 2011). These satellites capture images using spectral wavelengths in the visible bands of red, green and blue plus a near infrared band that reflect off the earth surface. However, in the case of *WorldView-2*, it takes images across 8 spectral bands covering the visible and near infrared range with the ability to identify features up to a depth of 30 m (DigitalGlobe, 2010). The visible – near infrared satellites provide a good source of data for environments such as mangrove extent or coral reef degradation over large or remote areas as a cost effective solution in managing changes in the environment (Klemas, 2011).

The other satellite sensors, such as microwave radiometers and scatterometers, can monitor changes in ocean health through measuring the different types of parameters outline in Table 2. They are an advantageous way of being able to monitor oceans and remote coastal areas over time (Brown et al., 2005; Klemas, 2011). This can help in a variety of ways such as by providing sea surface temperature or sea surface salinity to help in the monitoring of coral reef systems which are an important part of life in the oceans (Klemas, 2011).

Satellite sensors rely on three types of resolutions that can help in determining what a user is identifying, including spatial, spectral and temporal resolutions. Spatial resolution refers to the size of a pixel in an image with higher resolution images having smaller pixel sizes than low resolution. In habitat mapping a high resolution size like *WorldView-2* (0.50 m, 2 m) receives better quality images than *Landsat 7* (15 m, 30 m) satellite (Klemas, 2011). However larger pixel sizes such as in *Landsat 7* help it cover larger areas on earth in one image.

Spectral resolution is the number of specific wavelength intervals that it uses to when it takes the images. A high spectral resolution satellite like *MODIS* has thirty six bands that are in multispectral and thermal wavelengths, whereas *WorldView-2* has eight spectral bands in the multispectral wavelengths (Falkowski, Wulder, White, & Gillis, 2009; Klemas, 2011). Temporal resolution indicates the time it takes to revisit a site with the *WorldView-2* having a very short revisit time of just over a day (DigitalGlobe, 2010).

Classifications methods for remote sensing

Classification of remote sensing images involves assigning a class label to an image pixel. This can be done either by a supervised or an unsupervised classification model (Tso & Mather, 2009). Supervised models use identified pixels to train the classifier to help in determine the boundaries in each class. Whereas an unsupervised model uses the input data to determine the characteristics of each class and then assign a class to a pixel in the image (Tso & Mather, 2009).

Most classification methods rely on satellite imagery data to be adjusted so they can remove radiative transfer effects (Hochberg, 2011). To do this coastal habitats need to be adjusted for radiance, reflectance, atmospheric corrections and sun-glint on water so it is possible to identify benthic communities more clearly (Hochberg, 2011). Hedley, Harborne, & Mumby (2005) simplified a technique to remove sun glint and this has been done with positive results in a variety of studies such as Lobitz, Guild, Armstrong, Montes & Goodma (2008), J. M. Kerr (2010) in coral reef mapping and O'Neill, Costa, & Sharma (2011) in eelgrass mapping. This type of pre-processing helps in creating more accurate classifications (Hochberg, 2011).

There are many studies on use of classification models to classify high resolution satellite imagery with a particular focus on using a maximum likelihood classification especially in coral reef habitats (Andréfouët et al., 2003; Fonseca et al., 2010; Peter J. Mumby & Edwards, 2002). A study done on saltmarsh habitats by Cawkwell et al.

(2007) used the maximum likelihood classifications and found that it could be used to accurately classify habitat. However, overlapping pixels created confusion between some vegetation classes. These studies show that using supervised classification is an effective way of mapping habitats from training pixels.

Unsupervised classification models are generally considered less accurate as they rely on identifying the classes themselves however studies such as that by Ibrahim et al. (2009) found that they can be just as accurate when a suitable classification technique is applied. Though this study recognised that unsupervised classification might not replace supervised they pointed out that results can help in identifying pixels to be used in training them for supervised classifications (Ibrahim et al., 2009).

Remote sensing and geographic information systems for habitat classification

The integration of remote sensing with geographic information syatems (GIS) is useful for mapping changes in ecosystems overtime. This was done in a study by Ramachandran, Sundaramoorthy, Krishnamoorthy, Devasenapathy, & Thanikachalam (1998) to monitor changes in mangrove systems using satellite imagery and GIS. They used imagery from the *IRS* satellite and the *SPOT* satellite to identify change with the help of GIS.

A similar study was also done in Kenya on mangrove forests within a marine protected area. The study done by Kairo, Kivyatu, & Koedam (2002) successfully used GIS with aerial photography to determine the location of mangrove forest stands.

Improvement in software designed to process remotely sensed images such as *ENVI* by ITT Visual Information Solutions, and the amalgamation it has with GIS users, has led to many studies incorporating GIS with image processing software to monitor and map coastal environments (ITT Visual Information Solutions, 2007). One study by Hennig, Cogan, & Bartsc (2007) used hyperspectral imagery to analyse intertidal zones with the help of *ENVI 4.0* and identified that using it could greatly improve remotely sensed data in GIS.

Other uses of *ENVI* have been in mapping coastal wetlands (Wei & Chow-Fraser, 2007), impacts of climate change on coastal zones (El-Nahry & Doluschitz, 2009), and coastal terrain modelling (Hogrefe, Wright, & Hochberg, 2008). These studies, along with the improvements and increased amounts of remote sensing imagery and software designed to process it have made extracting geospatial information more viable to use in mapping of coastal areas (ITT Visual Information Solutions, 2007).

Decision support tools for conservation planning

Using mapped habitats with decision support tools is a useful way of figuring out complex problems centred around conservation planning (Ball, Possingham, & Watts, 2009). Decision support tools use targets that are set by the user to determine the best fit of where conservation priority is high or low. One such tool is *Marxan*, a widely used GIS integrated software for conservation planning around the world (Ball et al., 2009; Watts et al., 2009).

Marxan was initially designed to find representation of species and ecosystems in biodiversity conservation planning. Since its creation in 1999, it has been used and demonstrated on a broad range of planning challenges in spatially-explicit minimum set design (Ardron, Possingham, & Klein, 2010). This has been seen in *Marxan*'s use in coastal and marine natural resource management with many studies associated with marine reserve design (Airame et al., 2003; R. J. Smith, Eastwood, Ota, & Rogers, 2009) and conservation planning (R. J. Smith, Goodman, & Matthews, 2007; Visconti, Pressey, Segan, & Wintle, 2010).

Fernandes et al. (2005) used *Marxan* successfully in the rezoning of the Great Barrier Reef Marine Park. In this study *Marxan*, was used in multi-use zoning plans over the entire Great Barrier Reef to improve the network of no-take areas within the area. The *Marxan* algorithm identified 33% of the reef system that should be that in no-take areas. It used a variety parameters that included the number of planning units, cost of planning unit, important biodiversity feature layers and size of reserves (Ball et al., 2009).

Marxan has also been extended to be used with zones. The usefulness of this was shown by Klein, Steinback, Watts, Scholz, & Possingham (2010) as a way to provide conservation without impacting on fisheries production off the coast of California. The study used *Marxan* to identify four types of protected areas which produced areas where fisheries activities lost less than 9% of their value while meeting the conservation targets.

The idea behind using *Marxan* in reserve design is to solve the problem of locating the best representation of biodiversity while limiting the impact on possible costs from reserve placement (Game & Grantham, 2008). Data such as species, habitats, and/or other relevant biodiversity surrogates is inputted into *Marxan* which then aims to identify reserve systems that will meet the biodiversity targets that were set out by the user for minimum cost (Game & Grantham, 2008).

1.3 Three Kings Islands

New Zealand has many offshore islands that have limited spatial information describing the coastal habitats surrounding them because of their remoteness. One important offshore island that makes up its own coastal biogeographic region is the Three Kings Islands (34^{o} S 10’ 4”; 172^{o} E 6’ 11”), which is located 56 km north west of Cape Reinga at the tip of the North Island, New Zealand (F. Brook, 2003; Ministry for the Environment, 2011c).

The Three Kings Islands has a high level of endemism in marine species as well as unique terrestrial life (Bellingham, Wiser, Wright, Cameron, & Forester, 2010; F. Brook, 2003; V. Kerr, 2005; Richie). The islands are made up of the large Great Island (400 ha), North East Island, South West Island and West. It also includes the Princes Islands that is made up of five smaller islands and also several rocky outcrops that surround the islands (Black, Sporli, & Nicholson, 2008; F. Brook, 2003; Richie, 1997).

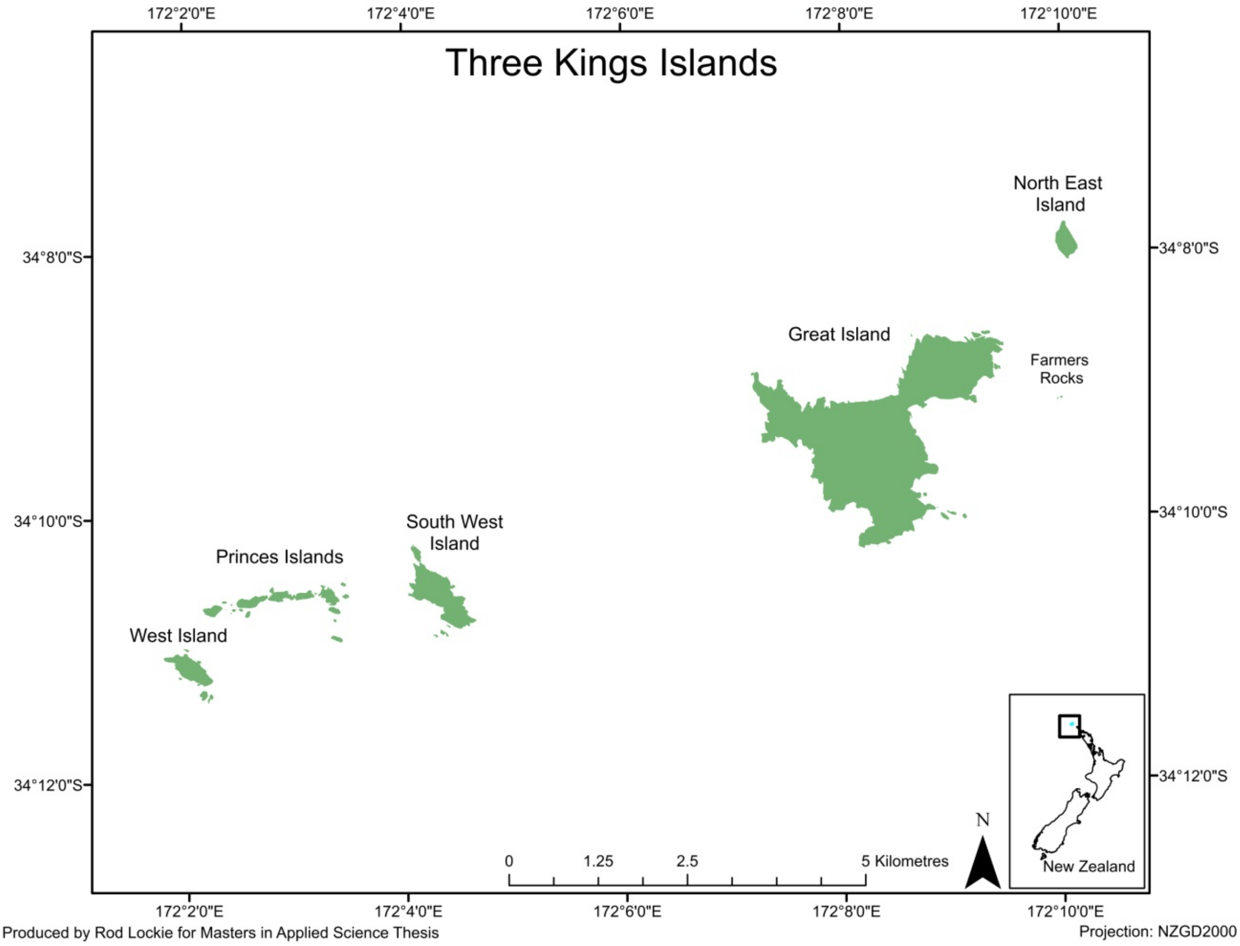

Figure 2. Three Kings Islands

The islands have a volcanic history and have been isolated from the NZ mainland for approximately 15 million years, however the last glaciation period would have seen the submarine plateau that they lie on separated from the rest of NZ by a strait of about 10 km wide (Bellingham et al., 2010; Nelson, Hancock, & Kamp, 1982; Nicholson, Black, & Sporli, 2008; Richie, 1997). It has had limited occupation by humans with permanent inhabitation ending around the 1840s (Richie, 1997). However, there was still considerable deforestation done while humans were living on the islands and after the 1840s, by the goats inhabiting them (Bellingham et al., 2010; F. J. Brook, 2003).

Since humans and goats have been completely removed from the islands, (in 1946 the islands were declared pest free), the regrowth in forests has been slow, however the isolation has still left many endemic species of trees, birds and other terrestrial species that includes endemic land snails and lizards (Bellingham et al., 2010; Brook, 2002b; Gill & Parrish, 2003; Richie, 1997). Because of this unique environment, the islands has been protected as a wildlife sanctuary through the declaration of a Nature Reserve by the Department of Conservation in 1995. The Nature Reserve limits accessibilty to the islands and by default, protect flora and fauna on the islands (Department of Conservation, 2011).

As a coastal island that has a large expanse of water around it, there are many species of seabirds that call the islands home. It supports large populations of Gannets and the Red Billed gulls which are one of New Zealand's largest roosting sites (Buddle, 1947; Department of Conservation, 2011; Ramsay & Watt, 1971). While it has numerous other birds on the islands that are also located on the mainland, it does have one of two breeding populations of Buller's Mollymawks in New Zealand (McCallum, Brook, & Francis, 1985; Ramsay & Watt, 1971).

This is supported by a marine ecosystem that provides habitats for an array of fish species and other marine organisms that take advantage of environmental features that help make it one of the more diverse marine ecosystems in New Zealand waters (Brook, 2002a; Francis, 1996; V. Kerr, 2005; Richie, 1997). One environmental feature of importance to the Three Kings Islands is the presence of an east to north-east flowing subtropical current known as the Tasman Front (Brook, 2002a; V. Kerr, 2005). The Tasman Front passes Three Kings Islands in the form of the east flowing East Auckland Current, which brings down warmer water, while the erratic south flowing West Auckland and the north flowing Auckland currents converge on the islands (F. Brook, 2003; Brook, 2002a; Morrison, 2005). These oceanographic conditions combined with a local upwelling, bring cooler water up from a depth of 100 m and help provide for a unique ecosystem that supports a high variety of marine life (F. Brook, 2003; Brook, 2002a; Morrison, 2005). This is evident in the makeup of warm temperate and subtropical species of algae with many of them being endemic to the area and support a high variety of fish (Adams & Nelson, 1985; F. Brook, 2003).

Most of the fish species in the area are from similar climes and can be found around the North Island coast. However, the islands also are missing some common species but makeup for it by having an abundance of rare fish species that are found in small numbers elsewhere (F. Brook, 2003; Brook, 2002a; Francis, 1996; Zemke-White & Clements, 2004). With the inclusion of benthic organisms, particularly molluscs, the water surrounding the islands sustain 25% endemism. The islands have the highest concentration of endemic species in areas shallower than 50 m than elsewhere in New Zealand (F. Brook, 2003).

The Three Kings Islands and nearshore waters are illustrative of a coastal classifications (as outlined in Table 1) representing a marine environment of varying depths and high exposure levels. This marine environment is an area of high concentrations of flora and fauna that is not protected by the Nature Reserve, which only encompasses the land and offers limited protection to the intertidal area as outline by the Reserves Act 1977 (Department of Conservation & Ministry of Fisheries, 2005).

1.4 Research problem and questions

In summary the Three Kings Islands have a unique mixture of terrestrial and marine biota that makes it an important area of New Zealand in terms of protection. As such this provides the basis for this research and the use of satellite remote sensing data that has been collected via the *WorldView-2* satellite and other sources of information.

This research will aim to identify areas of high importance through the use of satellite imagery, GIS and decision support tools at the Three Kings Islands. The research created a coastal and nearshore marine habitat classification of the Three Kings Islands using the eight multi-spectral bands of the *WorldView-2* satellite imagery. This was done through the use of remote sensing and GIS software that helped in the identification and mapping of habitats. The habitats were then used in conjunction with *Marxan*, a decision support tool, to identify reserve systems that met the needs for biodiversity protection within the Three Kings Islands coastal biogeographic region.

The questions below were used to address the research aims.

Question 1: Can *WorldView-2* satellite imagery be used to identify the coastal habitats of the Three Kings Islands coastal biogeographic region?

Question 2: Can the decision support tool, *Marxan*, be used with the coastal habitats in question 1 to select high conservation areas in the Three Kings Islands?

1.5 Structure of Thesis

I addressed the research questions by using remote sensing techniques to classify coastal habitats, which were then run through *Marxan* to identify areas of high conservation value within the area of Three Kings Islands.

In chapter 2, I described the methodology I used to acquire the satellite imagery and to prepare the data for processing the classifications. I described how I applied the unsupervised and supervised classification techniques to the imagery and then discuss the methods used for running *Marxan* with the Three Kings Islands habitat classifications.

In chapter 3 I presented the results of my classifications for both the marine and terrestrial environments and the accuracy of each. Then, I presented the final habitat maps that were used in *Marxan* and describe the conservation planning results that were found by using the scenarios of 10%, 20% and 30% targets for protection.

In chapter 4, I discussed my classifications and the accuracy of each method for habitat mapping. I then discussed the decision support tools and the implication for conservation management of remote locations in New Zealand. In chapter 5, I concluded with my findings of the questions that were answered. This was followed up with future recommendations that could be done in the Three Kings Islands coastal biogeographic region in chapter 6.

2. Methodology

2.1 Study Area

Located at 34° S 10’ 4”; 172° E 6’ 11”, the Three Kings Islands are 56 km to the northwest of the northern tip of New Zealand. It consists of five islands with small rocky outcrops in an area of 83 km^2. It is located in a remote location with limited opportunities to travel to the area for study and because of this provides a good opportunity to use satellite imagery as a means of habitat classification.

The entire biogeographic region covers an area of 2219 km^2; however for this study this was limited to a study area up to the 100 m depth contour or 111 km^2. The 100 m depth contour was chosen as the outer limit because the satellite imagery donated by *DigitalGlobe* did not cover the whole bioregion.

2.2 Image Acquisition

Images were taken by the *WorldView-2* satellite and provided by *DigitalGlobe* on two separate occasions. The first set of images were acquired by the satellite on the dates of 17th and 29th January 2010 at approximately 22:50 GMT. One of the images had a high proportion of cloud cover over Great Island which made it difficult to conduct a habitat classification in and around the island. The second set of images was acquired on the 4th of April 2011 at approximately 23:00 GMT. This was an image of all the islands with minimal interference from cloud cover. Also available was a high resolution quickbird colour image with no NIR that was not used in comparing classifications. However, it was used to check habitats for use with planning tools as the image was taken on a calmer day with limited sea surface interference.

Sensor Characteristics

WorldView-2 satellite images were used in this study (Table 3). The satellite was launched in 2009 offering high resolution images from 8 multispectral bands. This allows it to capture and discriminate areas of fine details such as ships, shallow reefs and individual trees. Another added advantage from other similar satellites is the revisit time where it is able to visit the same location in the world in about 1.1 days (DigitalGlobe, 2010).

Table 3. *WorldView-2* Specification (DigitalGlobe, 2010)

Resolution:	Panchromatic (450 – 800 nm): 50 cm Spectral: 1.84 m
Spectral Bands:	Coastal (400 – 450 nm), Blue (450 – 510 nm) Green (510 – 580 nm), Yellow (585 – 625 nm) Red (630 – 690 nm), Red edge (705 – 745 nm) NIR1 (770 – 895 nm), NIR2 (860 – 1040)
Slew Time:	300 km in 9 seconds
Swath Width:	16.4 km at nadir
Collection Capacity:	550,000 km^2 /day
Average Revisit:	1.1 days
Altitude:	770 km

2.3 Software

ENVI 4.8

ENVI 4.8 is image processing software, created by ITT Visual Information Solutions, that visualises, analyses and presents all types of data. The software includes spectral tool, geometric correction, terrain analysis, radar analysis, raster and vector capabilities. It is compatible with *ArcGIS* and supports a wide range of images from a diverse array of sources (ITT Visual Information Solutions, 2010).

ENVI 4.8 uses simple tools to easily process multiband images, spectral plots and regions of interest, while providing the display capabilities of geographic images. The software package includes functions and algorithms that help in the processing of images from start to finish (ITT Visual Information Solutions, 2010). Because of this and its compatibility with *ArcGIS* it was used for this research.

ArcGIS 10

ArcGIS is software used in geographic information systems (GIS) and used to compile and manage geographic information. It supports GIS applications such as mapping, data compilation, analysis, geodatabase management and geographic information sharing. Due to this, *ArcGIS* is a widely used software package that many GIS professionals use and one of the reasons why it was chosen for this research (ESRI, 2007).

Marxan

Marxan is a decision support tool in a wide variety of conservation planning, which can include reserve design, reporting on existing reserves and developing multiple-use zoning plans for natural resource management. This software was chosen for this research as it is flexible in use and can be applied to a wide range of problems and can be repeated to provide a large number of options of where reserves should be placed (The University of Queensland, 2008). It was used for this research to determine the best areas in and around the Three Kings Islands for a system of protected areas.

2.4 Data Preparation and Processing

Prior to using the images, I conducted geometric correction to align the image with the polygon maps of the islands. This was based on the datum WGS1984. Then each of the images was pre-processed using *ENVI 4.8* tools for radiance correction, dark pixel subtraction, removal sun-glint and masking. This was done before any classifications methods were applied and the process is outlined in Figure 3.

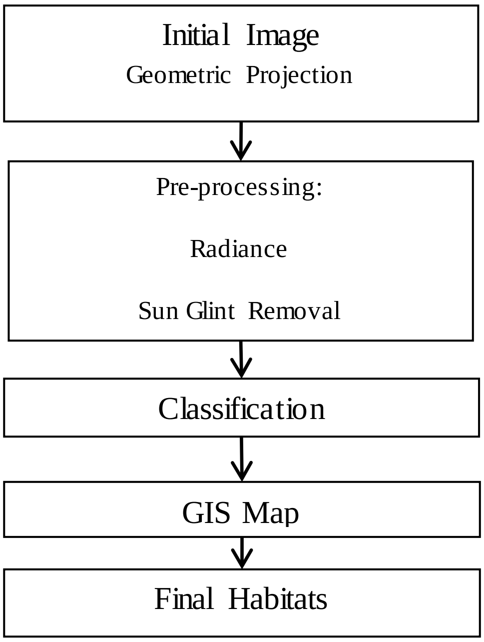

Figure 3. Flowchart showing methodology

Radiance Correction

Using *ENVI*, the data were converted from raw digital numbers in the original images to at-sensor radiance values (W m^{-2} sr^{-1} nm^{-1}) using equation 1 which is found in Updike & Comp (2010).

$$L_{\lambda Pixel,Band} = \frac{K_{Band} * q_{Pixel,Band}}{\Delta\lambda_{Band}} \qquad (1)$$

Where: $L_{\lambda Pixel,Band}$ represents top-of-atmosphere spectral radiance image [W -m^{-2} -sr^{-1} -μm^{-1}]; K_{Band} is the absolute radiometric calibration factor [W-m^{-2} -sr^{-1} -$count^{-1}$] for a given band; $q_{Pixel,Band}$ are radiometrically corrected image pixels [counts]; and $\Delta\lambda_{Band}$ is the effective bandwidth [μm] for a given band.

Sun-glint Removal

The images had sun-glint present and this was removed using the method obtained from Kerr (2010) who used a simplified model created by Hedley, Harborne, & Mumby (2005) from Hochberg & Atkinson (2003).

Using a radiance image, deglinting was done by using a sample region of interest in deep water with sun-glint to estimate linear relationship between the visible bands and the near infrared (NIR) bands. From this sample minimum NIR value was also identified to represent non-glint NIR. Using the following equation the image was corrected (J. M. Kerr, 2010).

$$L'_t = L_t - b \times (L_{t,NIR} - Min_{NIR}) \quad (2)$$

Where: L'_t is the deglinted radiance value; L_t is at-sensor radiance; b is the slope estimated by the linear regression; $L_{t,NIR}$ is the NIR radiance value; and Min_{NIR} is the minimum NIR value identified in the sample.

This sun-deglinting was only done to the images that were used in the classification of water habitats.

Atmospheric Correction

Dark pixel subtraction was used to atmospherically correct the *WorldView-2* images. This method assumes that the image pixels are in complete shadow, therefore the radiance received at the satellite is because of path radiance (Chavez, 1996; ITT Visual Information Solutions, 2010). This is combined with the fact that few targets on Earth's surface are absolute black (Chavez, 1996). The constant value is then used to subtract from a particular spectra removing the first-order scattering component. The method was performed using the feature available within *ENVI 4.8*.

Masking

A mask was created by separating land and sea using *ArcGIS* and *ENVI 4.8*. This was done by creating a polygon shapefile around the islands in *ArcGIS* then importing this shapefile into *ENVI 4.8* as an .evf file so a mask could be applied. This was done to have accurate classification models and remove land being classified as sea or vice versa.

Shadow and cloud were also masked at this time so as to not give false readings in the classification stages. This was done by identifying cloud and shadow in masked images separately in *ENVI 4.8* using the region of interest (ROI) tool. Then using the ROI selected and parallel classifications identify areas of cloud or shadow and using the result to create a mask.

2.5 Classification techniques

ENVI 4.8 supervised and unsupervised classification models were used to determine where habitats were found on the images. This was done by selecting areas where changes could be seen in the images for supervised classification. Regions of interest were then drawn within these areas to help in supervised classification models. Unsupervised classification was capped at fifteen classes in both K-means and ISODATA. This was done for both the land and sea images.

Supervised Classification Models

Three supervised classification methods from *ENVI 4.8* were used in the classification of habitats in the images. These were minimum distance, mahalanobis distance and maximum likelihood.

Maximum Likelihood

The maximum likelihood classification is the most common method used in supervised classification. It assumes that the statistics for each class is normally distributed and calculate the probability a single pixel belongs to specific class. It classifies all pixels unless a threshold is set, which in this case, was not set. The pixels classified are allocated a class that is the maximum likelihood (ITT Visual Information Solutions, 2010; Richards & Jia, 2006)

Minimum distance

Minimum distance classification model uses the average vector of each endmember and calculates the Euclidean distance from each unknown pixel to the mean vector for each class. The image pixels are classified to the nearest class that was selected via the ROIs, however some pixels will be unclassified if they fall outside the specified range (ITT Visual Information Solutions, 2010; Richards & Jia, 2006).

Mahalanobis Distance

The ENVI classification method of mahalanobis distance was used to classify region of interest. This method is a direction sensitive classifier that uses statistics for each class. Similar to the maximum likelihood classification method however it makes the assumption that all class covariance's are the same and therefore a faster method. This method is outlined in Richards & Jia (2006) and employs the use of ROI tool on ENVI. ROIs were created using images and identifying differences in colour between locations, i.e. dark patches close to shore.

Unsupervised Classification

K-means Classification

K-means classification method is an unsupervised method that uses a minimum distance technique where all initial class means are evenly distributed in the image before being iteratively clustered. In this study the number of classes was set at ten, five iterations, and a threshold of 5% from the options available on *ENVI* (ITT Visual Information Solutions, 2010).

ISODATA Classification

ISODATA classification is similar to K-means classification in that each class is evenly distributed in the images and it uses a minimum distance technique. However, the iterative classes are split, merged or deleted using an input threshold which was, in this case, set at 5% (ITT Visual Information Solutions, 2010).

2.6 Classification processing

The marine and terrestrial classifications were applied to three different groups of bands to identify locations that matched the ROIs chosen. ROIs were chosen using the satellite imagery to distinguish between the types of benthic habitats in the near shore environment. Furthermore, ROIs were chosen from visual observations made during a visit to the Three Kings Islands while on the *R.V. Tangaroa* as well as using literature on the vegetation of Three Kings Islands (Bellingham et al., 2010).

The three band groupings were based on the traditional four band visible NIR found in the majority of other high resolution satellites as well as the new bands used in the *WorldView-2* satellite (J. M. Kerr, 2010). One grouping used all eight bands from the satellite, whereas the other two groupings were based on the traditional red, green, blue and NIR bands, and coastal, yellow, red-edge and NIR2. Each of these groupings was put through the supervised and unsupervised classification tools provided in *ENVI 4.8*. This was done to compare the new spectral bands that *WorldView-2* uses to capture images in the visible wavelengths.

Marine Classifications

There were five important ROIs chosen to distinguish between benthic habitats, while the other ROIs were included as they were considered factors that could give false readings when the classifications were done (Table 4). The five important ROIs were used in all classifications to identify benthic habitats of the near shore regions and comparable to classes in the MPA classifications from Table 1 in chapter 1 from exposed intertidal and subtidal habitats. These were selected by visual observations while on board the R.V. *Tangaroa* and reviewed literature (F. Brook, 2003).

Table 4. Habitat type and associated ROI colour.

Habitat Type	Region of Interest Colour
Sandy reef	Red
Deep Rocky reef	Blue
Rocky reef	Cyan
Shallow Rocky reef	Yellow
Seaweed	Magenta
Sea	Purple
White-water	White
Unclassified	Black

The band groupings chosen were based on *WorldView-2*'s eight spectral bands. One grouping was done using all eight bands, whereas the other two groupings were based on the original red, green, blue and NIR bands, and coastal, yellow, red-edge and NIR2. Each of these groupings was put through the supervised and unsupervised classification tools provided in *ENVI 4.8*. This was done to compare the new spectral bands that *WorldView-2* uses to capture images in the visible wavelengths.

Terrestrial Classification

These ROIs were created on the land images to be used to represent different ground cover types. These were selected by difference in land cover from the satellite images, visual interpretations while on the board the *R.V. Tangaroa* and reviewed literature on vegetation found on the islands (Bellingham et al., 2010). Table 4 shows the habitat types that were identified with the ROIs.

Table 5. Habitat type and region of interest colour.

Habitat Type	Region of Interest Colour
Scrub	Red
Forest / Scrub	Blue
Forest	Green
Bare Rock	Cyan
Bare Ground	Yellow
Guano	Maroon
Boulders / Gravel	Purple
Seaweed	Magenta
White-water	White
Unclassified	Black

The terrestrial classifications used the same band groupings as was used to do the marine classifications.

Confusion Matrix

Confusion matrix was used to calculate the accuracy of the classification. This determines the accuracy of a classification by comparing the ROIs selected with the classification results. This was done to get the producer and user accuracies which were compared using the kappa coefficient as well as the overall accuracy. The kappa coefficient measures the proportional improvement by the classifier over random assignment classes (ITT Visual Information Solutions, 2009). This was done through *ENVI 4.8* using the confusion matrix tool. This was a technique similar to that used by Kartikeyan, Majumder, & Dasgupta, (1995) and Baraldi, Bruzzone, & Blonda, (2005) who used it to test for accuracy with land cover classification with limited or no ground truthing points.

Majority Analysis

From the classification results the most accurate identified by the confusion matrix was run through the *ENVI 4.8* majority analysis post classification method to remove false pixels and replace them with larger groupings of classes. To do this a kernel size of 3 by 3 and a centre pixel of one inside the kernel (ITT Visual Information Solutions, 2010). This was done to allow smoother classifications for GIS analysis.

GIS Analysis

Marine Classifications in GIS

The classes from the marine classifications described above, were converted to polygon shapefiles in *ENVI 4.8* to be used in *ArcGIS*. During the transfer from *ENVI 4.8* to *ArcGIS* classifications of white-water and sea were removed as these were not required for any analysis in *ArcGIS*.

Once converted and transferred to GIS the marine habitat classes were clipped with bathymetry data. The bathymetry data was overlaid in a polygon to clip the rock and sand layer anomalies down to 30 m. It was assumed anything outside this was a false classification as *WorldView-2* imagery cannot penetrate to depths greater than this (DigitalGlobe, 2010). The underwater rock classifications were then separated into distinct depth classes with the help of the bathymetry data.

Terrestrial Classifications in GIS

The classes from the terrestrial classifications were converted to polygon shapefiles in ENVI to be used in *ArcGIS*. However, areas that would be affected by tidal fluctuations such as seaweed patches, boulders and gravel were added to the marine classifications. The seaweed patches were combined with the seaweed class obtained from the marine classifications.

Once the GIS analysis was done through editing of marine and terrestrial class shapefiles, they were converted from polygons into a raster images so they could easily be used within *Marxan*.

2.7 *Marxan* analysis

To use *Marxan*, planning units needed to be created in the form of a uniform grid. These planning units were then used to identify the coverage of habitats within them. The planning units size and shape are determined by the user for which ever works best for the data they have on hand for analysing (Game & Grantham, 2008).

For this study, grids of hexagons were chosen as it was decided that they would be able to fit better with the islands coastlines. They were generated with *ArcGIS* 10 using *Repeating Shapes* extension tool created by Jenness (2011). Each hexagon had an area of one hectare that was overlaid on to the habitat maps with the length of the side of the hexagons set a 62 metres. This divided up the study area into11,541 hexagon shaped planning units. The planning unit of one hectare was chosen as it was seen as an appropriate size that could meet the conservation goals of the research within the study area (R. J. Smith et al., 2009).

Boundary length was calculated using the extension, *Marxan ArcGIS* 10 *Boundary tool*, from ABP Marine Environmental Research Limited (ABPmer, 2011). This tool creates a boundary file where the cost is the length of the boundary and is shared by each planning unit of selected feature class. This included 21 features, which were made up of the terrestrial and marine habitats as well as depth. These were used as surrogates, within *Marxan* to represent the biodiversity to meet the conservation goals.

Each planning unit along with biodiversity surrogate was then tested against three scenarios. These were 10%, 20% or 30% of habitats that are within a planning unit. Using the inputs of the land and sea habitats with depth *Marxan* was run to determine the best areas for protected areas. The scenarios were run 100 times using simulated annealing and normal iterative improvement. *Marxan* was done with 10 million iterations that are used to identify a planning unit at random that may or may not have already be used in a reserve system (Figure 4) (Game & Grantham, 2008).

This gave an output of suggested reserve sites within the Three Kings Islands biogeographic regions that are irreplaceable and thus should be included in a reserve system.

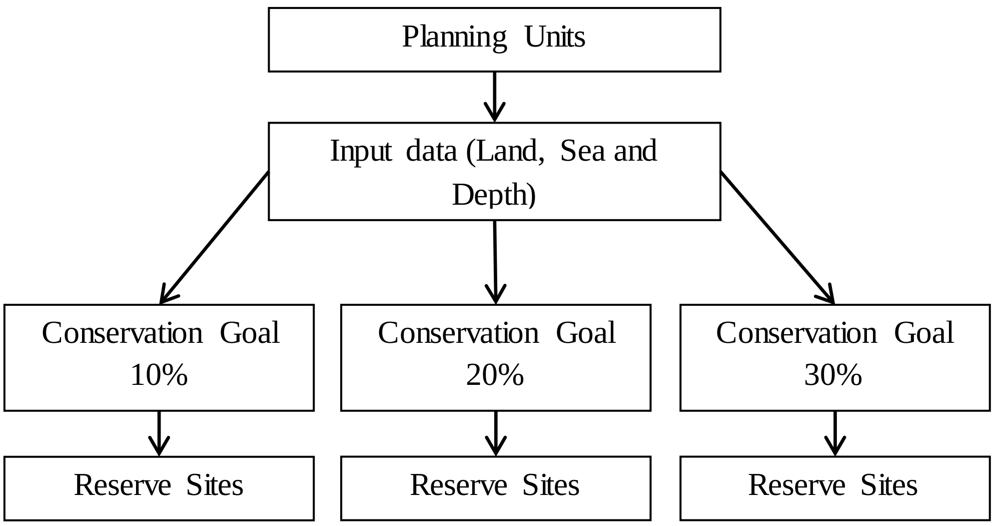

Figure 4. Flowchart of *Marxan* methodology

3. Results & Discussion

3.1 Classifications

Marine Classifications

Unsupervised Classifications

The unsupervised classifications that were used showed very little useable data after both techniques were used. No habitats of importance were shown from the images available (Figure 5 and as a result they were not used in any analysis in *ArcGIS*.

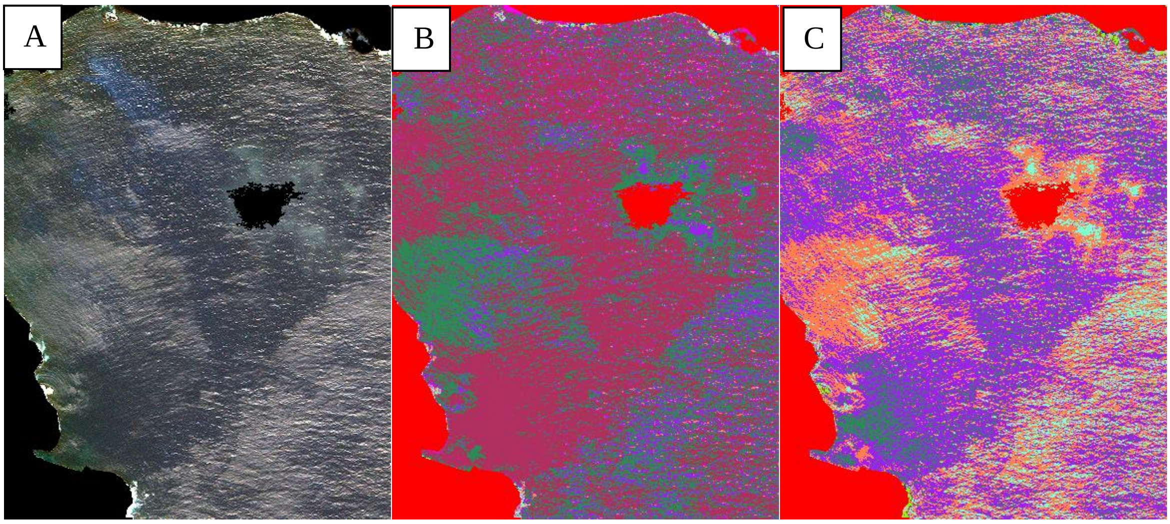

Figure 5. Unsupervised classification of marine habitats with Southeast Bay. (A. Colour image of land; B. ISODATA; and C. K-means)

Supervised Classifications

The minimum distance classifications showed good results when using all band groupings except the group of blue, green, red and NIR (Figure 6). However these results were not accurate in determining deeper rocky reefs (blue) as these areas were misclassified in all images (Figure 6). Rocky reefs (yellow and cyan) and sandy reefs (red) were easily identified from the image in the band groupings of coastal, yellow, red-edge and NIR2 and all the bands combined (Figure 6).

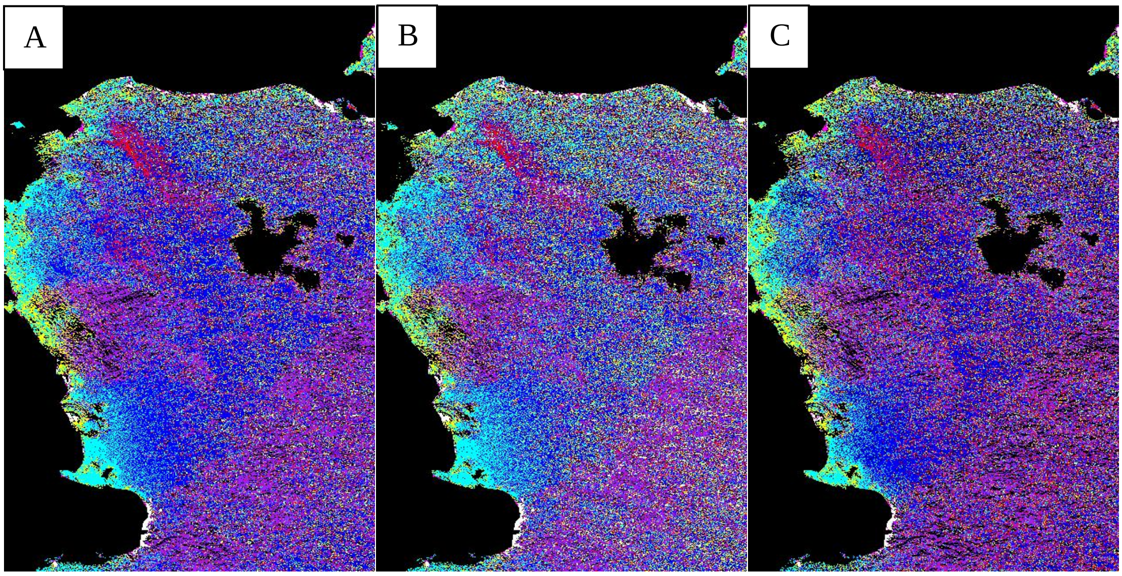

Figure 6. Minimum distance classification at Southeast Bay showing habitat classes. (A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2)

Mahalanobis distance classification showed good results in only one of the band groupings. This was the group with all bands (Figure 7). The grouping of coastal, yellow, red-edge and NIR2 showed locations in deeper water with habitats marked as shallow rock (yellow). Whereas the blue, green, red and NIR showed promise. However there were still anomalies of shallow rock in deeper water (Figure 7). The sand bottom (red) was easily identified by the grouping with all bands and could also be identified in the blue, green, red and NIR group but this was mixed with shallow rocks (yellow) (Figure 7).

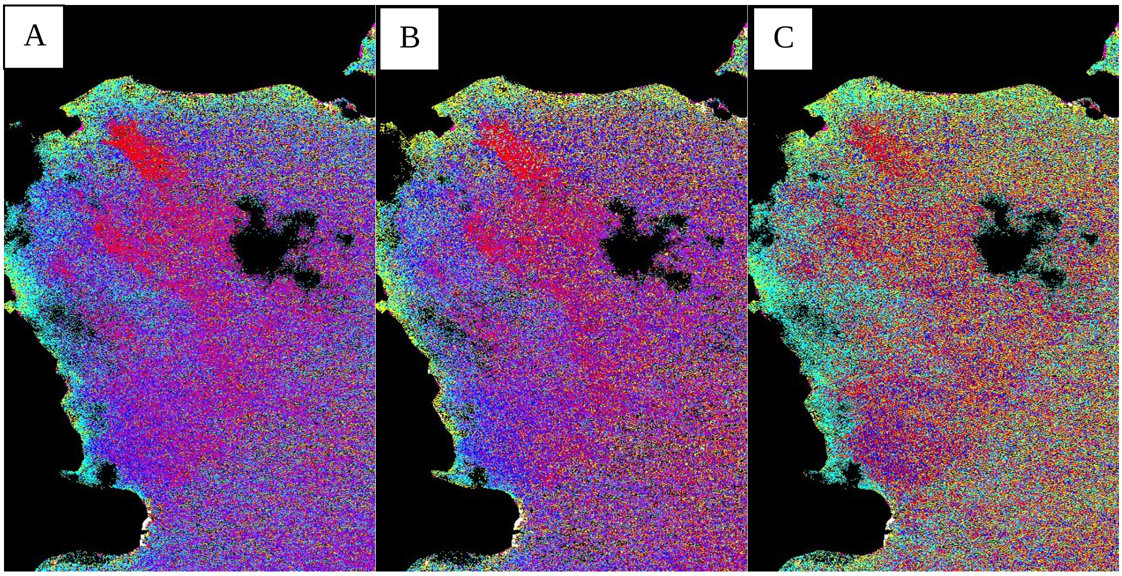

Figure 7. Mahalanobis distance classification at Southeast Bay showing habitat classes. (A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2)

The final supervised classification of maximum likelihood showed a more accurate classification using all bands than the other two groups (Figure 8). It showed shallow rock (yellow) where the sea was in coastal, yellow, red-edge and NIR2 group (Figure 8). This was the same with the group with red, blue, green and NIR in it. However they all showed the location of the sand bottom (red) with more accurate classification of this shown in the group with all bands present (Figure 8).

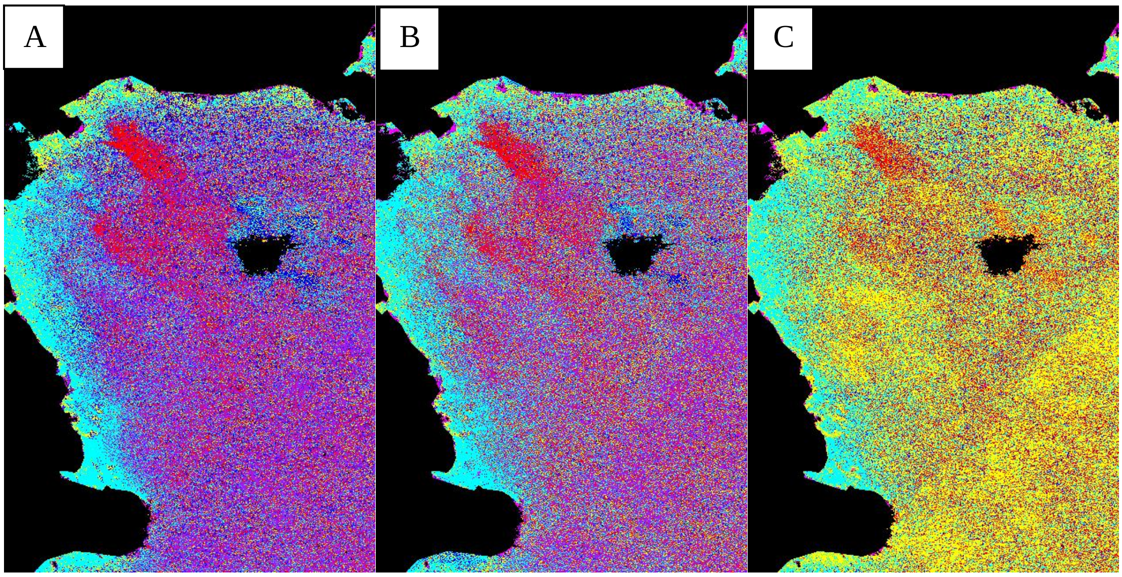

Figure 8. Maximum likelihood classification at Southeast Bay showing habitat classes. (A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2)

From these results it was found that using all bands during the classification techniques was better at classifying habitats. The results of the classifications also showed that, other than in the minimum distance technique the bands of red, green, blue and NIR gave a more accurate results over marine classifications (Figures 8).

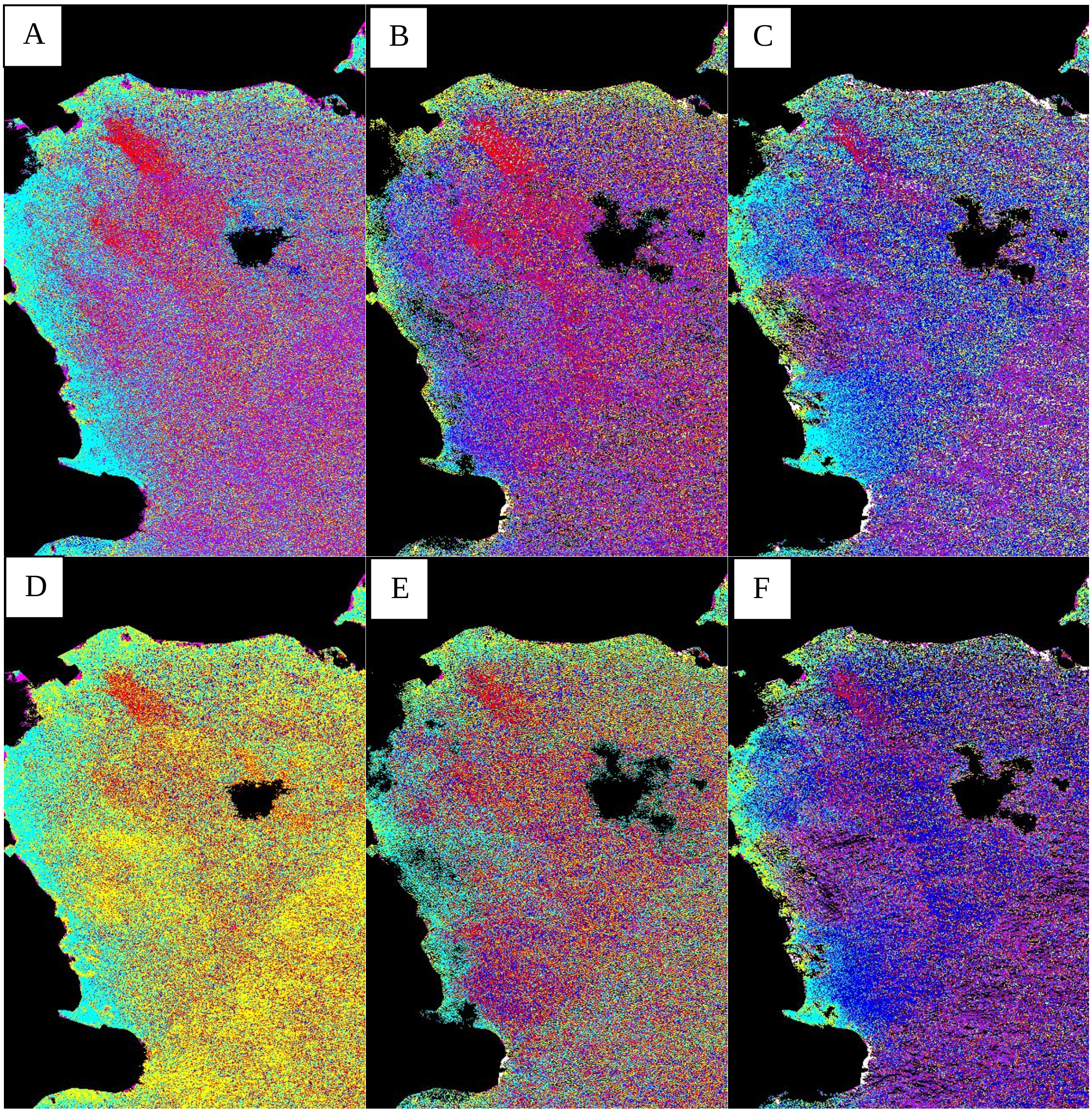

Figure 9. Southeast Bay showing comparison between red, green, blue and NIR and coastal, yellow, red-edge and NIR2. (A. Maximum likelihood (red, green, blue and NIR). B. Mahalanobis distance (red, green, blue and NIR). C. Minimum distance (red, green, blue and NIR). D. Maximum likelihood (coastal, yellow, red-edge and NIR2). E. Mahalanobis distance (coastal, yellow, red-edge and NIR2). F. Minimum distance (coastal, yellow, red-edge and NIR2))

From the classifications it was seen using all bands that the maximum likelihood identified the majority of habitats with a better classification of seaweed (magenta), sand (red), and shallow rocks (yellow and cyan) than the other classification techniques (Figure 10). However, deeper rocks (blue) were not always identified accurately enough using this classification (Figure 10). This also shows where cloud shadow has affected the result in deeper water in maximum likelihood (Figure 10).

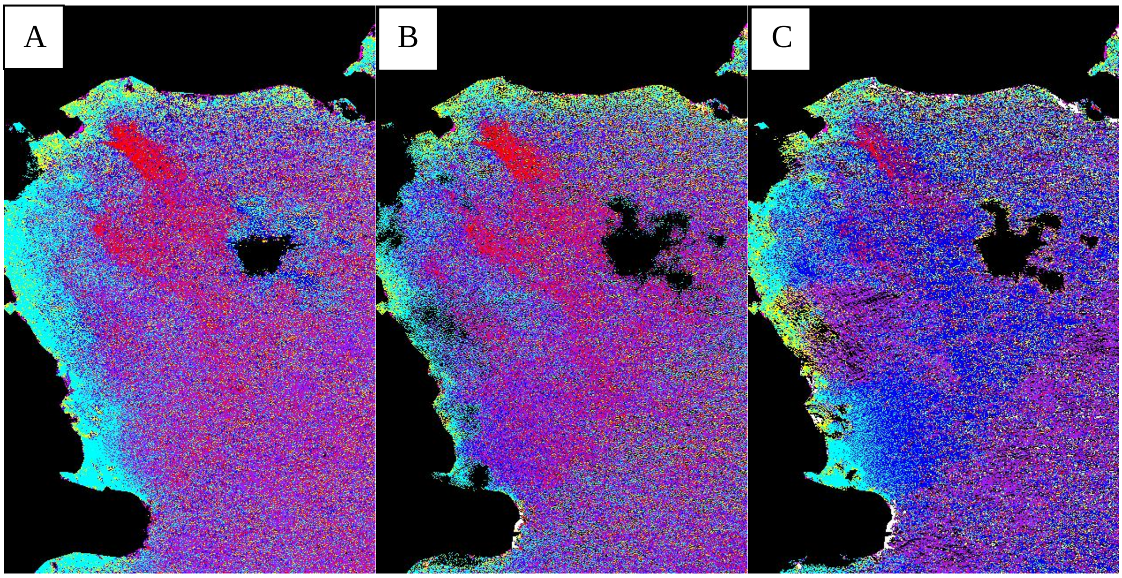

Figure 10. Southeast Bay showing classifications using all bands showing seaweed (magenta), sand (red), shallow rock (yellow and cyan) and deep rocks (blue). (A. Maximum likelihood; B. Mahalanobis distance; C. Minimum distance)

The accuracy of the results from Figure 10 are shown through the use *ENVI*'s confusion matrix in Table 6. Maximum likelihood classifications were more accurate than the other classification techniques used with a total accuracy of 70.74%. The classifications of mahalanobis distance and minimum distance only show an accuracy of just above 50%. From the confusion matrix results it was concluded that maximum likelihood was the better classification technique. However, the kappa coefficient has a very low agreement for all the classification techniques between producer accuracy and user accuracy.

Table 6. Confusion matrix results of classification techniques

Classification Type	Class	Producer Accuracy (%)	User Accuracy (%)	Overall Accuracy	Kappa Coefficient
Minimum Distance (all bands)				51.65%	0.0163
	Unclassified	0	0		
	Sand	45.17	0.8		
	Rock	31.85	0.2		
	Shallow Rock	47.22	1.55		
	Rock	54.41	1.72		
	Sea	51.61	99.79		
	White-water	100	3.37		
	Vegetation	100	94.74		
Mahalanobis Distance (all bands)				54.58%	0.0187
	Unclassified	0	0		
	Sand	75	1.06		
	Rock	16.07	0.16		
	Shallow Rock	57.05	2.39		
	Rock	58.14	0.8		
	Sea	54.5	99.80		
	White-water	96.35	68.84		
	Vegetation	100	41.67		
Maximum Likelihood (all bands)				70.74%	0.0495
	Unclassified	0	0		
	Sand	75.97	1.28		
	Rock	25.41	0.74		
	Shallow Rock	56.91	2.1		
	Rock	73.53	2.48		
	Sea	71.17	99.88		
	White-water	100	14.55		
	Vegetation	100	2.69		

From these results the maximum likelihood classifications were processed with majority analysis on the sand, seaweed, and rock classifications to remove false single pixels and merge them together with larger single classes (Figure 11).

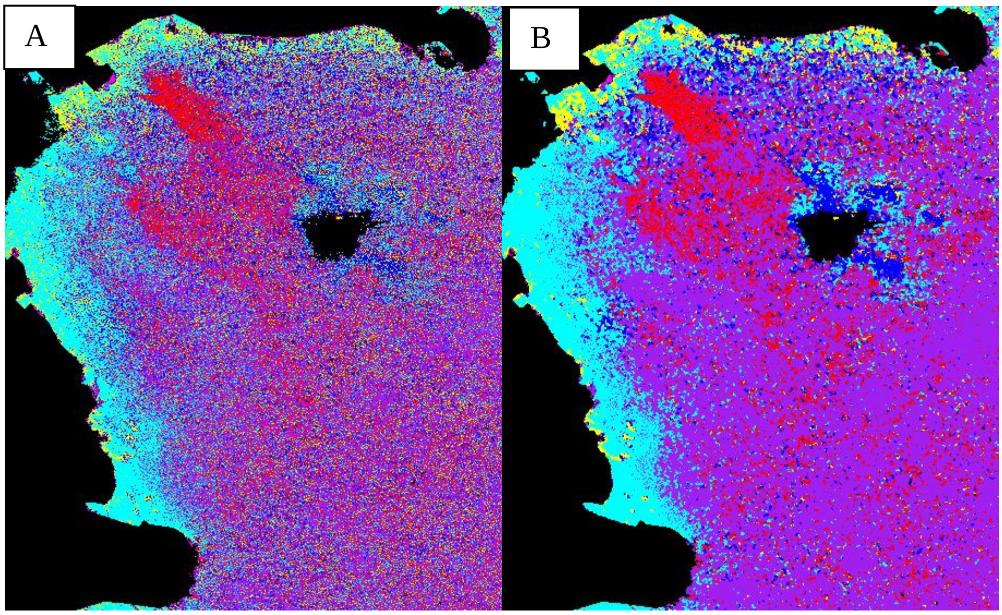

Figure 11. Maximum likelihood classification adjusted with majority analysis. (A. Maximum likelihood; B. Majority analysis of maximum likelihood)

The maximum likelihood classification was then applied to the other imagery from the *WorldView-2* satellite to include areas that were hidden by cloud cover. This gave similar results of the above; however it also filled in some gaps of the marine habitats that were masked out by cloud from the other imagery. These classes were then converted to shapefiles to be used in *ArcGIS*.

Terrestrial Classification

Unsupervised Classifications

The unsupervised classifications that were used showed very little useable data after both techniques were used. However, using ISODATA was able to slightly distinguish between forest and scrub. Though, ISODATA classified seaweed as scrub as well as some areas of bare ground as forested areas (Figure 12). Due to these results they were not used in any analysis in *ArcGIS*.

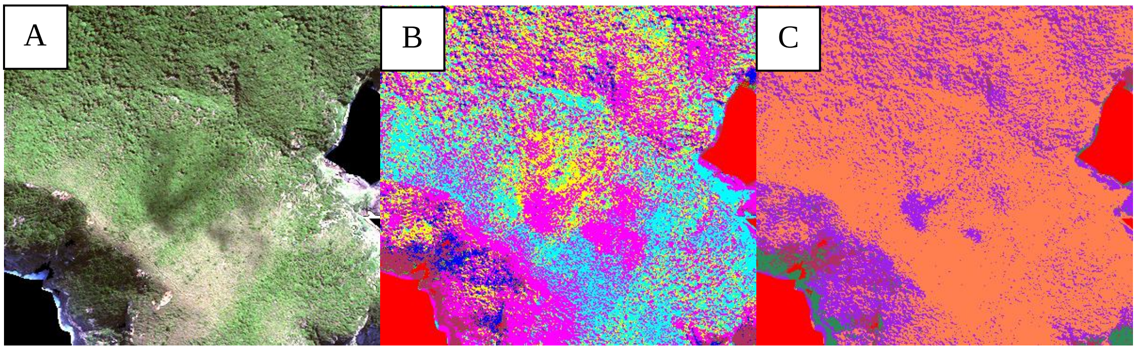

Figure 12. Unsupervised classifications of terrestrial habitats. (A. Colour image of land; B. ISODATA; and C. K-means)

Supervised Classifications

Minimum distance classification was inaccurate in classifying the majority of terrestrial habitats from the region of interests and gave a good result for the forested regions (blue and green) however, scrub (red) and bare ground (yellow) was often confused between each other (Figure 13). Guano (maroon) and bare ground (yellow) were also confused with each other (Figure 13).

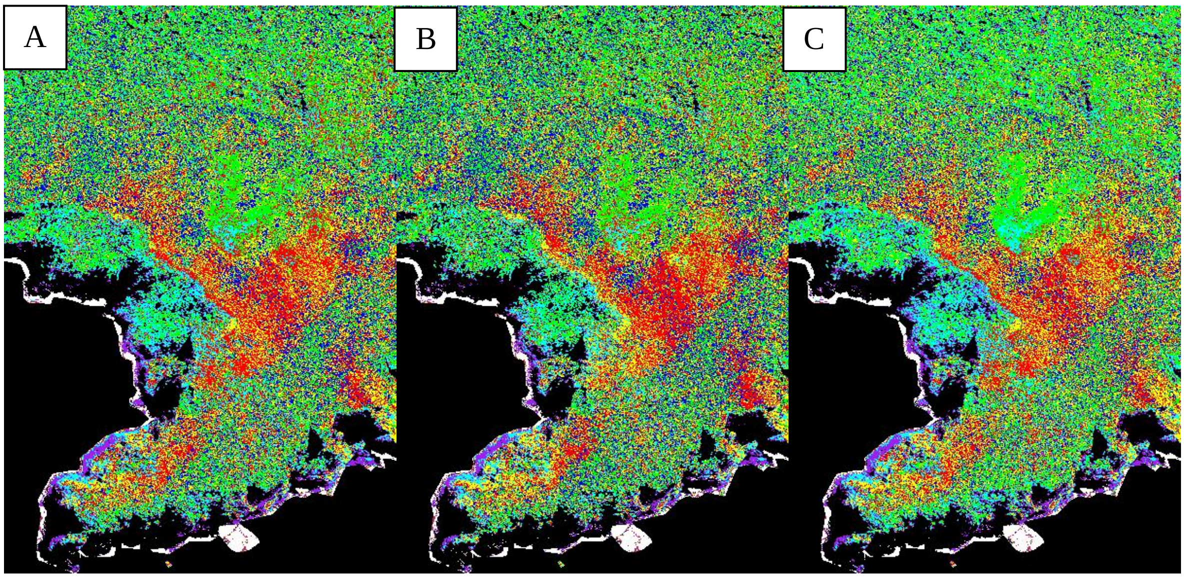

Figure 13. Minimum distance of Great Island south showing scrub (red), forested areas (blue and green), and bare ground (yellow). A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2.

The classification method of mahalanobis distance showed reasonable classification in identifying scrub (red) and forested areas (green and blue). It also distinguished areas of bare ground (yellow) and rocks (cyan). The best group of bands that identified the majority of classes was red, green, blue and NIR (Figure 14). This group was to able differentiate more precisely between scrub (red) and bare ground (yellow).

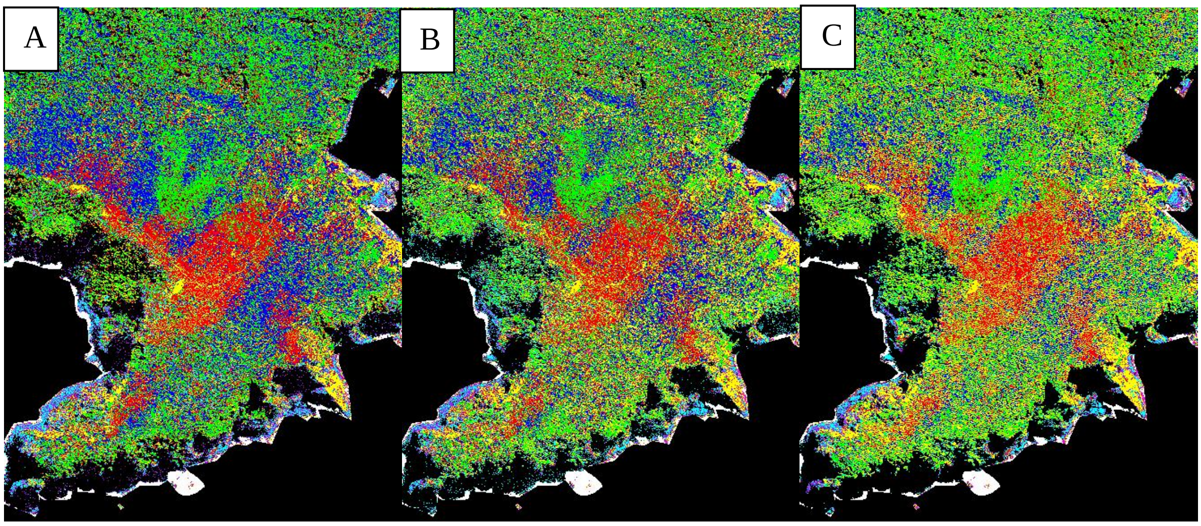

Figure 14. Mahalanobis distance of Great Island south showing scrub (red), forest (blue and green), bare ground (yellow), and rock (cyan). A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2.

The mahalanobis distance classification method was also able to identify dense seaweed patches (magenta) on the shore (Figure 15). These patches were obvious in two groups of bands; however the band group of red, green, blue and NIR showed seaweed patches that were not able to be distinguished as other habitat types (Figure 15).

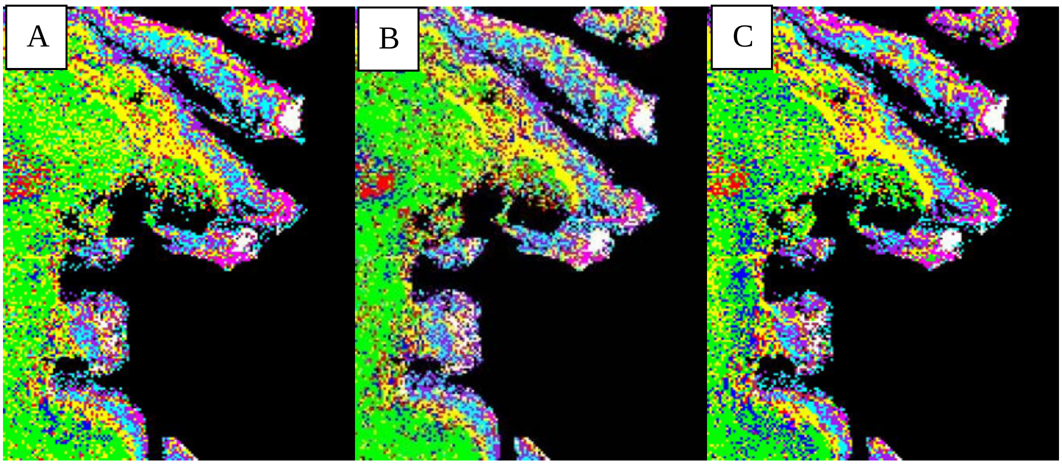

Figure 15. Classified seaweed patches (magenta) identified using mahalanobis distance technique. (A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2).

The other important habitat which is the bird roosting sites or guano (maroon was identified well from bare ground (yellow) in the classifications though it was discerned better using all bands (Figure 16).

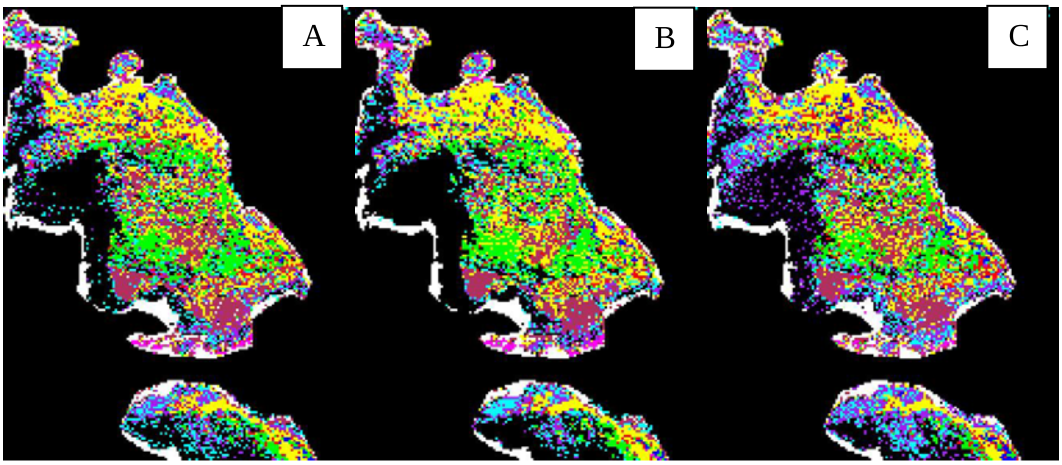

Figure 16. Classification of guano (maroon) distinguished from bare ground (yellow) using mahalanobis distance technique. (A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2).

The final classification technique of maximum likelihood gave the best results when compared to all other supervised classification techniques. This was obvious with the selection of scrub (red) and forested areas (blue and green) (Figure 17). However some shadowed areas of rock were misclassified as boulders (purple) on the band groupings of red, green, blue and NIR, and also on coastal, yellow, red-edge and NIR2 (Figure 17).

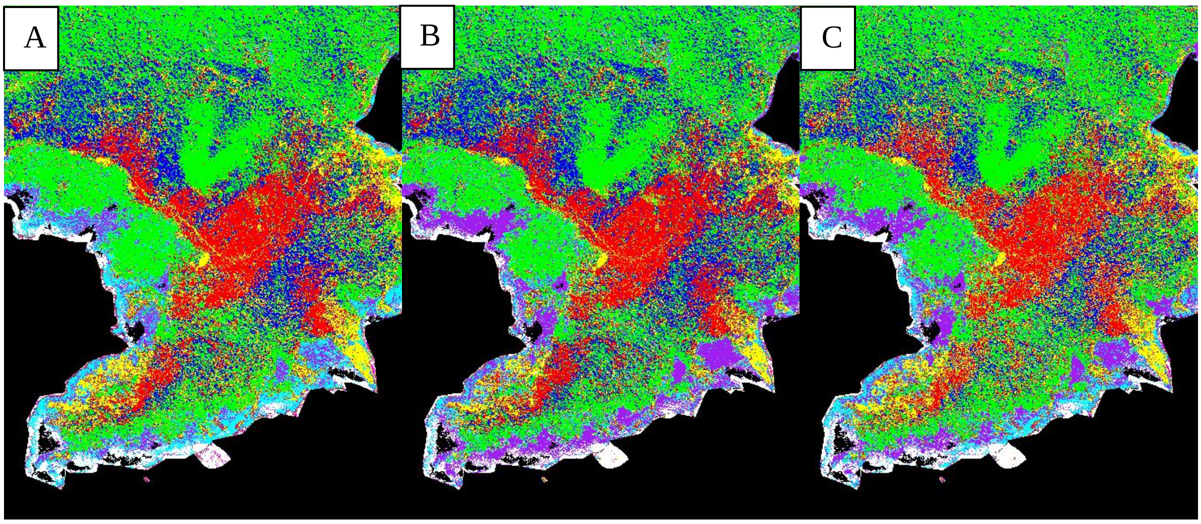

Figure 17. Maximum likelihood of Great Island south showing scrub (red) and forested areas (green and blue). Also shadowed rock classified as boulders (purple) in B and C. (A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2).

The maximum likelihood classification technique was also good at identifying guano classes using all the bands. However, other groups were unable to distinguish between bare ground (yellow) and guano (maroon) (Figure 18).

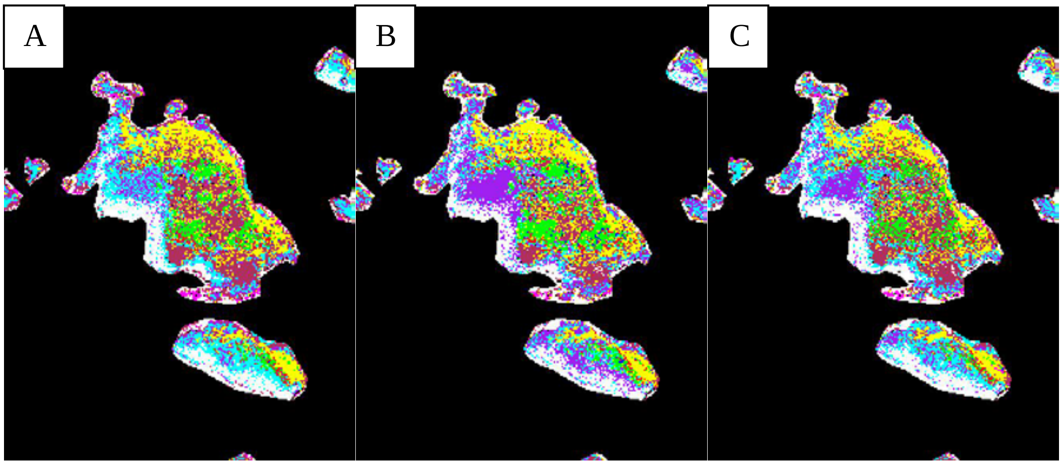

Figure 18. Maximum likelihood showing Princes Islands with guano (maroon) class. Also seaweed patches (magenta) can also be seen around island. (A. All bands; B. red, green, blue and NIR; and C. coastal, yellow, red-edge and NIR2).

From these results the majority of classifications were more accurate when using all bands, however, using minimum distance showed that classifications done with red, green, blue and NIR was better in determining scrub from bare ground rather than using all bands (Figure 19). Though when compared to the other classification techniques it was found that using maximum likelihood was a better fit in identifying classes from the region of interests (Figure 19).

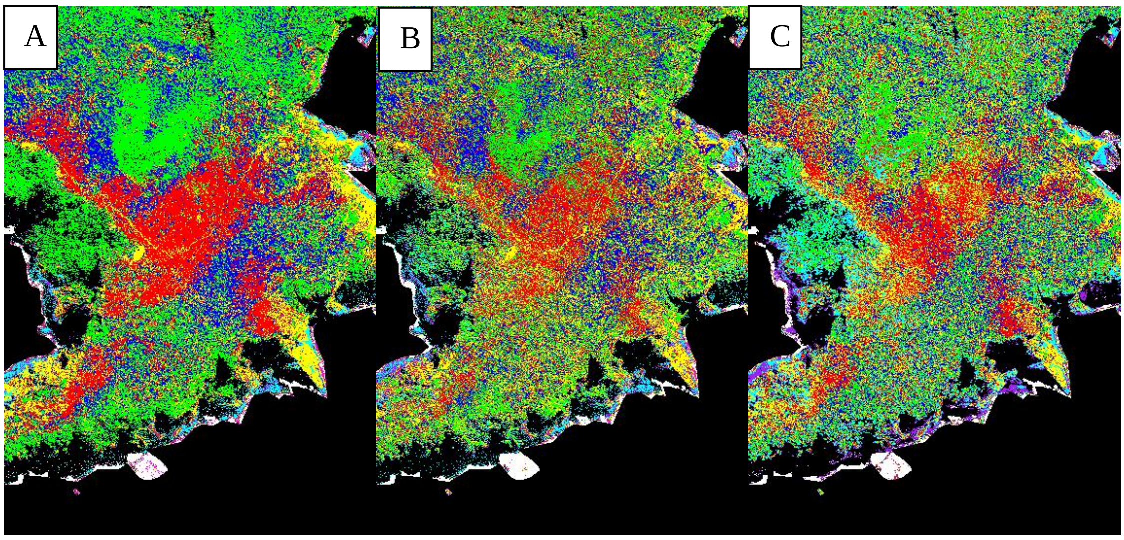

Figure 19. Great Island south showing scrub and forested areas (red, green and blue) with bare ground (yellow). A. Maximum likelihood (all bands). B. Mahalanobis distance (all bands). C. Minimum distance (red, green, blue and NIR).

Figure 19 shows that the maximum likelihood classification is better equipped to classify regions from the islands. Table 7 shows this with an overall accuracy of 87.30%, which is a lot higher than the minimum distance and mahalanobis distance shown. The kappa coefficient of the maximum likelihood (0.8454) also shows a high agreement whereas minimum distance and mahalanobis show moderate agreement between producer accuracy and user accuracy.

Table 7. Confusion matrix results of terrestrial classifications

Classification Type	Class	Producer Accuracy (%)	User Accuracy (%)	Overall Accuracy (%)	Kappa Coefficient
Minimum Distance (all bands)				61.22%	0.5401
	Unclassified	0	0		
	White-water	98.58	97.21		
	Scrub	67.05	74.9		
	Forest	58.71	93.75		
	Scrub/Forest	51.35	14.07		
	Bare Ground	66.58	34.9		
	Guano	47.87	79.42		
	Seaweed	73.17	90		
	Boulders	55.34	20.73		
	Bare Rock	59.7	69.89		
Mahalanobis Distance (all bands)				67.99%	0.6181
	Unclassified	0	0		
	White-water	97.14	92.31		
	Scrub	68.82	70.07		
	Forest	62.29	90.32		
	Scrub/Forest	63.51	18.58		
	Bare Ground	81.11	50.95		
	Guano	67.33	87.52		
	Seaweed	92.68	99.13		
	Boulders	60.49	23.85		
	Bare Rock	63.63	82.12		
Maximum Likelihood (all bands)				87.30%	0.8454
	Unclassified	0	0		
	White-water	99.58	95.92		
	Scrub	91.14	97.14		
	Forest	90.51	98.62		
	Scrub/Forest	82.43	37.65		
	Bare Ground	91.3	76.15		
	Guano	86.27	94.31		
	Seaweed	96.75	96.75		
	Boulders	74.65	94.51		
	Bare Rock	86.58	41.58		

From the results of the confusion matrix it was determined that the best classification technique to use for the terrestrial habitats was the maximum likelihood. This was put through the majority analysis as shown in Figure 20. From the majority analysis it was then transferred to *ArcGIS* as shapefiles.

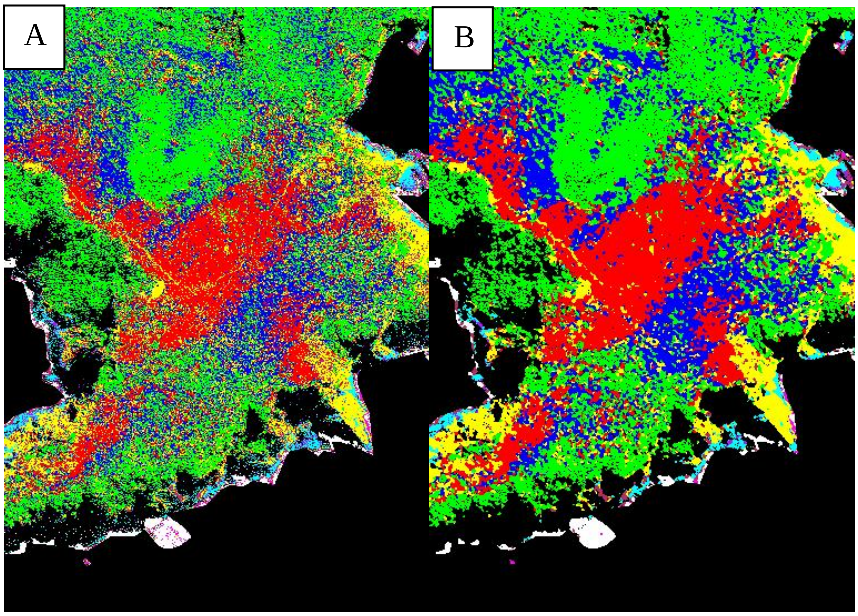

Figure 20. Maximum likelihood and the majority analysis of Great Island south. A. Maximum likelihood. B. Majority analysis.

Final Classification Map

Figure 21 shows the final classification of habitats of terrestrial and marine with the added depth contours that were used for the *Marxan* analysis. All habitats were converted into a raster file that is split between terrestrial and marine. The terrestrial habitats from the classifications have been edited with the combining of the classes of forest / scrub habitats with the forest class. This also saw the moving of the seaweed and boulders / gravel habitats which were added to the marine habitats.

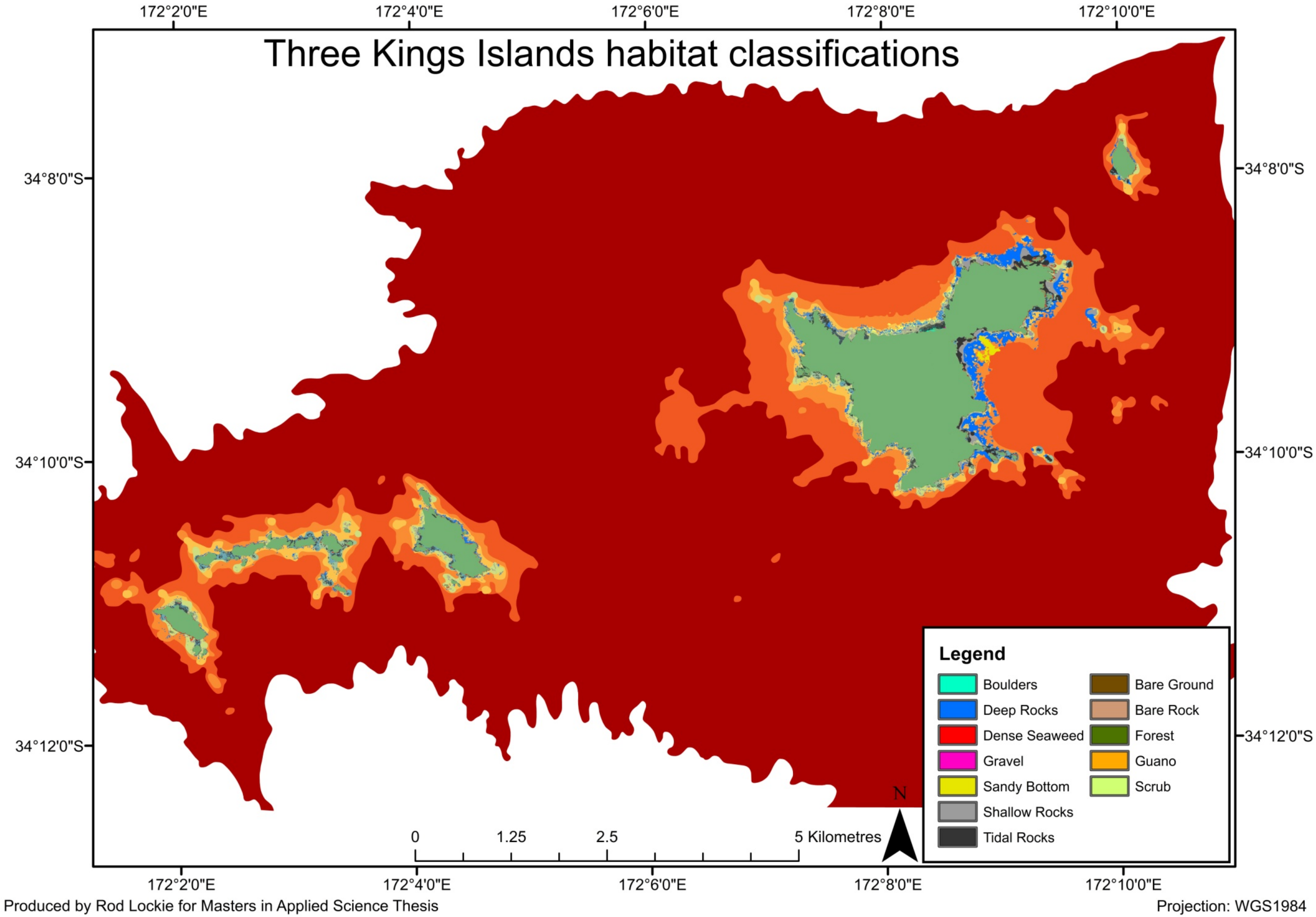

Figure 21. **Final habitat map of the terrestrial and marine habitats showing depth contours.**

3.2 *Marxan* analysis

Marxan created three summed solutions relating to the scenarios of 10%, 20%, and 30% protection. I mapped these solutions by planning unit to visualise the irreplaceability of certain habitats around the Three Kings Islands. This was seen to be around South East Bay and North West Bay, which showed high irreplaceability in these regions in the 10%, 20% and 30% scenarios (Figure 23). In the 30% scenario, the regions of high irreplaceability were viewed in the largest area mostly within the region of Great Island. The Princes Islands had a small number of areas that were of moderate irreplaceability with it showing up more in the 10% and 20% scenarios rather than in 30%.

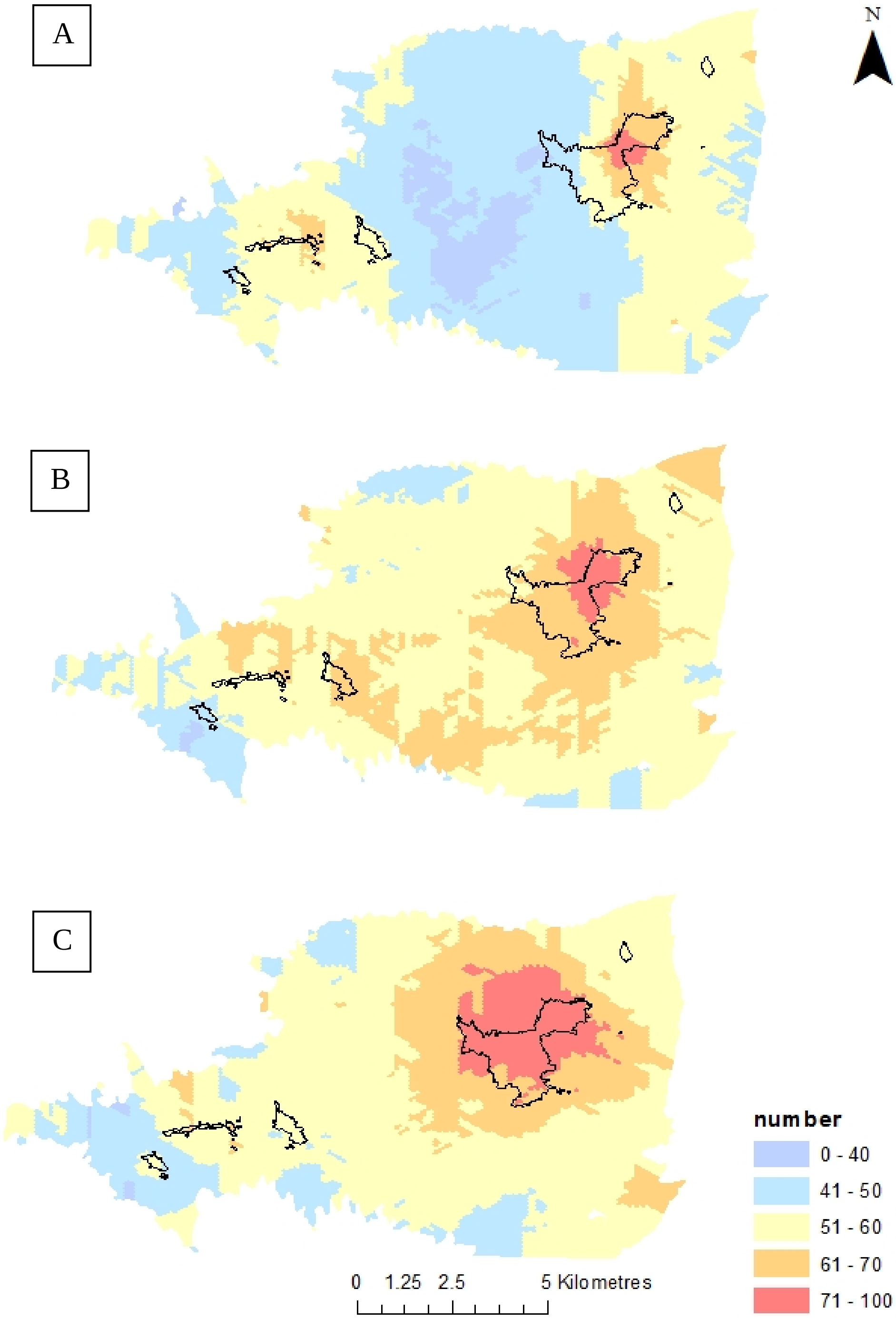

Figure 22. **Summed solution showing the number of times each planning unit appeared in 100 different scenarios identified by *Marxan*. (A. Scenario of 10%. B. Scenario of 20%. C. Scenario of 30%.)**

Scenario of 10%

Of the 10% scenario there was 80 planning units recognized as a highly irreplaceable areas using *Marxan*. This covered 0.69% of the planning regions that were shown on the map in an area of 8000 km^2. The next level of high conservation added another 28,610 km^2 (Table 6). These were found mostly in an area of Great Island that overlooks South East Bay. However, some of these were identified within eastern islands that make up the Princes Islands (Figure 22).

Table 8. Conservation value of planning units based on *MARXAN*'s summed solution output using a 10% target

Conservation value (number of times selected)	number of planning units	area (km^2)	percentage of planning region (total 11541)
Highest conservation value (71 - 100)	80	8,000	0.69%
High conservation value (61 – 70)	500	28,610	4.33%
Above average conservation value (51 – 60)	4741	450,416	41.08%
Average conservation value (41 – 50)	5428	522,633	47.03%
Low (0 to 40)	792	78,054	6.86%

Scenario of 20%

In the 20% scenario 235 planning units were recognized as highly irreplaceable areas from 100 runs. The highly irreplaceable regions covered an area of 23,499 km^2, of which was 2.04% of the planning region. This was increased with 2943 planning units from high conservation values that increased the percentage of the planning region to 27.54% (Table 6). It identified that the locations of Great Island as well as the bays of

South East and North West Bay held regions with very high irreplaceability levels (Figure 22).

Table 9. Conservation value of planning units based on *MARXAN*'s summed solution output using a 20% target

Conservation value (number of times selected)	number of planning units	area (km^2)	percentage of planning region (total 11541)
Highest conservation value (71 - 100)	235	23,499	2.04%
High conservation value (61 – 70)	2943	288,813	25.50%
Above average conservation value (51 – 60)	7203	693,930	62.41%
Average conservation value (41 – 50)	1123	98,988	9.73%
Low (0 to 40)	37	3,526	0.32%

Scenario of 30%

The final scenario of 30% showed after a 100 runs that 898 planning units were distinguished areas of high irreplaceability. They covered a region of 89,799 km^2 that was focused on Great Island and the surrounding bays. This was 7.78% of the planning region which increased to 30.72% after the input of high conservation levels (Table 8).

Table 10. Conservation value of planning units based on *MARXAN*'s summed solution output using a 30% target

Conservation value (number of times selected)	number of planning units	area (km^2)	percentage of planning region (total 11541)
Highest conservation value (71 - 100)	898	89,799	7.78%
High conservation value (61 – 70)	2648	259,952	22.94%
Above average conservation value (51 – 60)	6361	611,528	55.11%
Average conservation value (41 – 50)	1591	143,786	13.79%
Low (0 to 40)	43	3,692	0.37%

The most effective scenario of the three was 30% with large areas of highly irreplaceable regions that surrounded Great Island. The regions selected encompassed the majority of habitats that were classified and if chosen for protection would help in the conservation of the region (Figure 22).

4. Discussion

4.1 Satellite Remote Sensing in Coastal Environments

The Three Kings Islands coastal habitats have been identified through the use of satellite imagery with habitats identified within the terrestrial and marine zones. The habitats that were derived from the region of interests were more likely to be identified when using the classification results of maximum likelihood with all the bands available from the *WorldView-2* satellite. The unsupervised classifications in the marine habitats were inaccurate and were not able to determine habitats within the study area. However, in the ISODATA for terrestrial habitats there was a possibility that habitats could be determined.

Band Combinations

From the results it was determined that the classifications using the groups of four bands of red, green, blue and NIR, and coastal, yellow, red-edge and NIR2 were not considered as accurate as using all bands in the *WorldView-2*. This was because they showed variation in the classifications of habitats that did not correlate well with where they were shown on map. This was seen more so in the new bands of coastal, yellow, red-edge and NIR2 in the marine habitats, where habitats such as rock were seen in deeper water. However, the band groups with the red, green, blue and NIR, which are available in other high resolution satellite images, showed similar results than the results when using all bands there were still some anomalies picked up. Collin and Planes (2011) also observed this when they compared the eight bands of *WorldView-2* with the four bands of *Quickbird-2* in tropical coastal habitats. They showed that classifications were done better when using the *WorldView-2* satellite, which they concluded to be due to using the added four bands in conjunction with the normal bands.

Supervised Classification Techniques

In mapping the habitats with all the available bands from *WorldView-2* the supervised classifications techniques showed reasonable accuracy within the minimum distance and mahalanobis distance. In the marine environment, sand habitats were identified over both these classification techniques with good accuracies. While in the terrestrial environments, habitats of forest and scrub they showed reasonable producer accuracy in the majority of classifications. However, using the maximum likelihood, more marine and terrestrial habitats were classified with better results shown by the confusion matrix.

The confusion matrix result clearly demonstrated that out of all the classification techniques the maximum likelihood gave the best accuracy. This was seen in the marine habitats with an overall accuracy of 70.74% as well as in the terrestrial habitats with an accuracy of 87.30%. However, with the marine habitats the kappa coefficient (0.0495) showed a very poor agreement between the producer and user accuracies, which suggests that there are disparities between the classifications observed in these habitats (Baraldi et al., 2005; Girard & Girard, 2003). In the terrestrial habitats the kappa coefficient (0.8454) showed a high agreement in producer and user accuracies that suggests that classifications observed are most likely correct (Girard & Girard, 2003).

From the accuracies determined by the confusion matrix it was shown that the maximum likelihood method was able to distinguish the region of interests selected with a better coverage than other classifications. This is comparable to other coastal habitat studies that have compared the use of classifications which have found that using maximum likelihood is more accurate than most other classification techniques

(De Roeck et al., 2008; Tong et al., 2004). As a result, this one of the reasons that this technique is widely used in classifying habitats compared to the other techniques (Ozesmi & Bauer, 2002).

However, as the images with most coverage of the Three Kings Islands were captured during the winter months when rough sea was present, some areas in the marine habitat were affected by white-water coming off the rocks. This presented some problems with classifications and resulted in poor delineation of marine habitats within these areas.

The habitats represented from the classifications were displayed in ArcGIS and the marine habitats were found to be similar to those outlined by the Department of Conservation and the Ministry of Fisheries (Department of Conservation & Ministry of Fisheries, 2008). These habitats outlined in Table 1 (Chapter 1) as high exposure in the intertidal and shallow subtidal areas and were identified within the marine environments from the image classification results.

4.2 conservation planning tools

Conserving the Three Kings Islands and the variety of habitats found within the biogeographic region is one of the last steps of providing protection to the species there. Using *Marxan* and the classified habitats from satellite imagery I have identified regions that could be used in any conservation strategy that is employed by the management authority of the biogeographic region.

The results of the *Marxan* analysis selected regions in the vicinity of Great Island with all scenarios identifying regions that were considered irreplaceable by the software. Of the scenarios used, the 30% scenario was more widespread and covered the majority of Great Island and the surrounding bays. This area covered the majority of habitats such as rocks, boulders, seaweed, and sandy bottom.

The other two scenarios of 10% and 20% identified a smaller area around Great Island that was irreplaceable. However, this was complimented with a small pocket of high conservation value around the Princes Islands. This is an area that includes large populations of seabird nesting sites. If the area was placed under marine protection it would cover only a small number of other habitats compared to areas of high irreplaceability that are found on and around Great Island.

When using the three *Marxan* solutions that were run with the habitat data provided by the classifications a very distinct area was identified by all three scenarios. The scenarios, however, had differences between the sizes of the area that was designated as irreplaceable with it progressively getting larger as the percentage of representation changed. This larger area within the scenario of 30% was a result of the requirement that more habitats are essential in meeting the target from the scenario (R. J. Smith et al., 2007).

These scenarios were used as targets for the representation of habitats within a possible reserve site in the Three Kings Islands. As outlined by Pressey, Cowling, & Rouget (2003) targets are a useful tool for the conservation planning in that they provide decisions that can be used in accountability and defensibility of an area. This was also seen by Tallis, FerdaÑA, & Gray, (2008) when *Marxan* was applied to coastal areas that included the terrestrial and marine environments in conservation planning. The targets produced results from limited knowledge that was collected via satellite imagery which was able to provide a reasonable coverage of habitats that would be found in and around the Three Kings Islands. However, with this limited knowledge it can provide a basis for any new information that is collected to be used within the targets and be incorporated into the conservation strategy (Pressey et al., 2003).

From this it is important to understand that the scenarios targets were used to provide an important aspect in the conservation of the Three Kings Islands coastal biogeographic region. However, with added information and changes in conservation goals the targets can fluctuate as they are used in management.

5. Conclusions

Satellite imagery from *WorldView-2* was successful in the identification of coastal habitats. Using the derived coastal habitats with decision support software, I was able to successfully identify high conservation areas. The results of the classifications showed the added advantage of using the eight band range of the *WorldView-2* satellite when compared to using just four bands of either red, green, blue and NIR from other high resolution satellites.

Using the separate classification techniques to distinguish habitats within the biogeographic region demonstrated the benefits that come from using the maximum likelihood technique with good overall accuracy from the confusion matrix. By using all the available bands with maximum likelihood a habitat map was created for the Three Kings Islands for use with decision support tools.

Using *Marxan* with this habitat map allowed me to successfully identify high conservation areas. The most significant area of high conservation seen in the vicinity of Great Island within the Three Kings Islands coastal biogeographic region. This was shown to be of high conservation value in all of the scenarios (10%, 20% and 30%) that were used.

The 30% scenario selected the largest areas of irreplaceability. The area covered the bays of South East and North West surrounding Great Island, which included a wide range of habitats identified by the satellite imagery. This area would provide a good representation that could be built into any future considerations of a possible marine protected area. This showed that using data identified via satellite imagery is helpful in identifying possible areas to be used in a network of reserves in remote regions such as the Three Kings Islands.

Though this research has demonstrated the benefits in using satellite imagery in remote areas there are still advantages that come from visiting a site and ground truthing the results. Unfortunately in locations such as the Three Kings Islands, extensive field work is not always possible due to a variety of reasons including cost and time.

This research will provide future studies of the Three Kings Islands coastal biogeographic region with data that could be helpful in developing future sampling protocols, building a reserve network and targeting knowledge gaps. In addition, decision support software allows for the inclusion of more data to be added as it becomes available. This research also provides a basis for more coastal habitat mapping studies to be done on other remote areas requiring a reserve network by using imagery from a high resolution satellite. For example this could be used on other offshore biogeographic regions in New Zealand waters that have had limited accessibility and thus limited information about coastal resources.

6. Future Recommendations

This study demonstrated the possibility of using high resolution satellite imagery for mapping coastal habitats and providing a basis for creating a system of marine protected areas using decision support tools.

The results of this thesis recommend a combined marine and island protected area should include the location directly surrounding Great Island. A reserve network around Great Island would provide some protection to the high level of endemism in the marine and island flora and fauna that is found within the Three Kings Islands coastal biogeographic region. This area would include at least 30% of the marine and terrestrial habitats identified in this thesis. The research also recommends that a marine protected area should be placed around the smaller islands within in the region.

In addition, targeted insitu ground truthing needs to be conducted to further validate the results of the coastal habitat classification. This would strengthen the knowledge of the Three Kings Islands and produce a more thorough reserve network.

This dataset needs to be combined with offshore underwater habitat data collected by NIWA (R.V. *Tangaroa* – 23/03/2011 to 8/04/2011) for a more detailed conservation planning assessment of the entire coastal biogeographic region of the Three Kings Islands.

Human use, such as commercial, recreational fishing and tradit7ional, should be assessed and included in the *Marxan* models to determine optimal reserve designs while minimising cost to the users of the region. *Marxan* with Zones should be applied across the islands and marine regions to investigate the possibility designing a multiple use marine park planning with different combinations of MPA's.

Finally, similar methods for coastal habitat classification and conservation planning assessments should be trialled in other offshore remote locations in New Zealand Waters, e.g. The Snares and Sub-Antarctic Islands.

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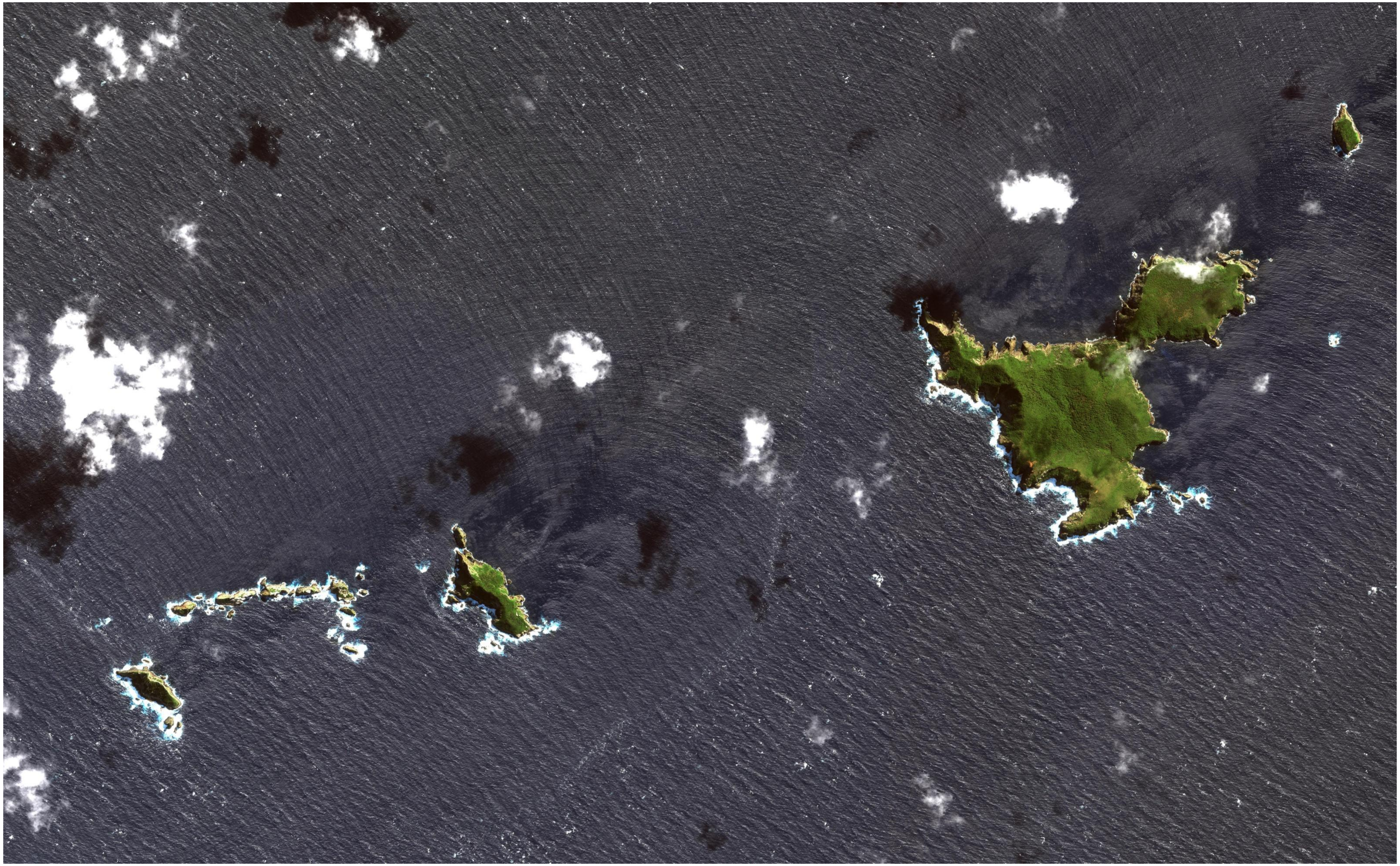
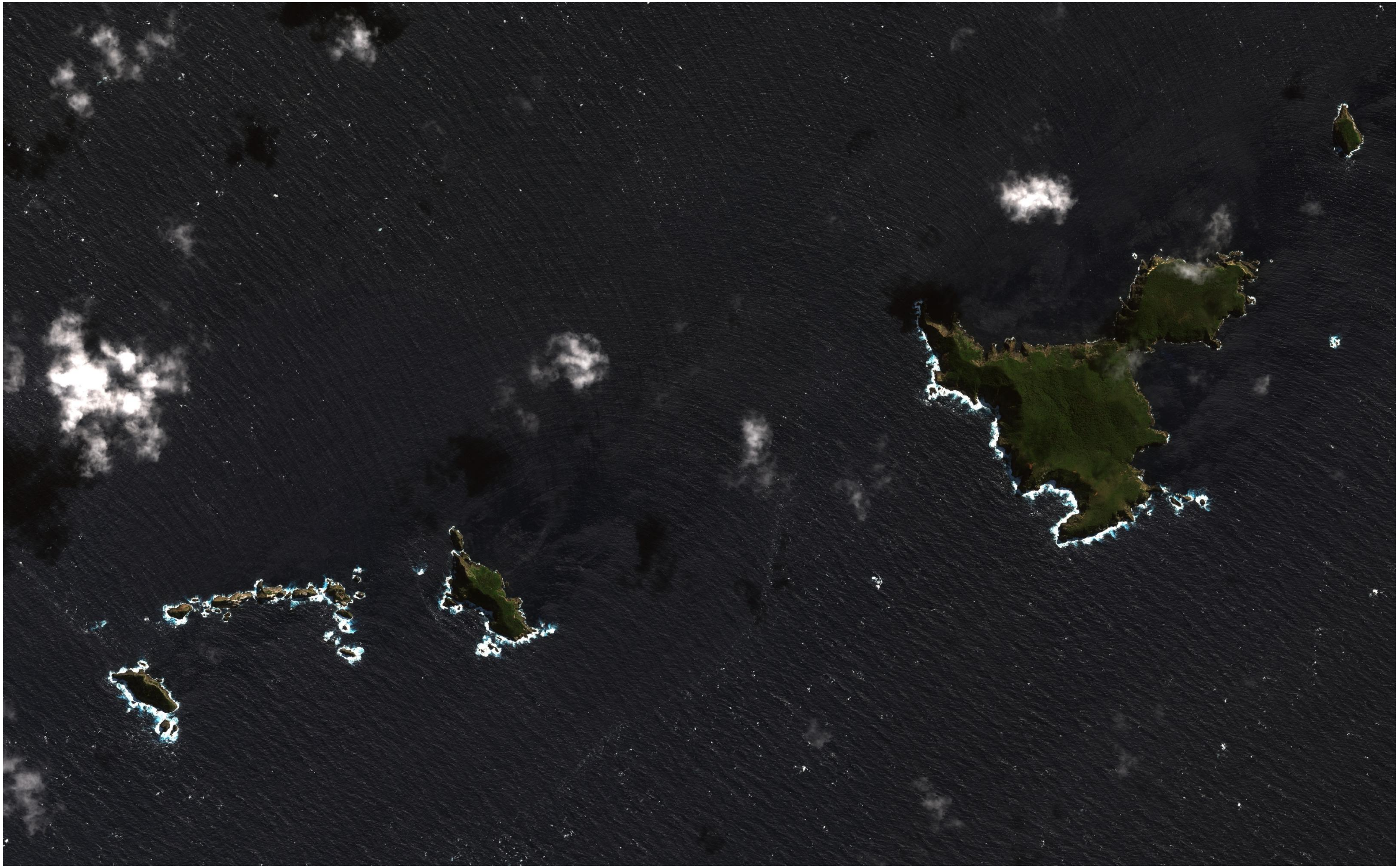
Appendix 1. Original images and preprocessing

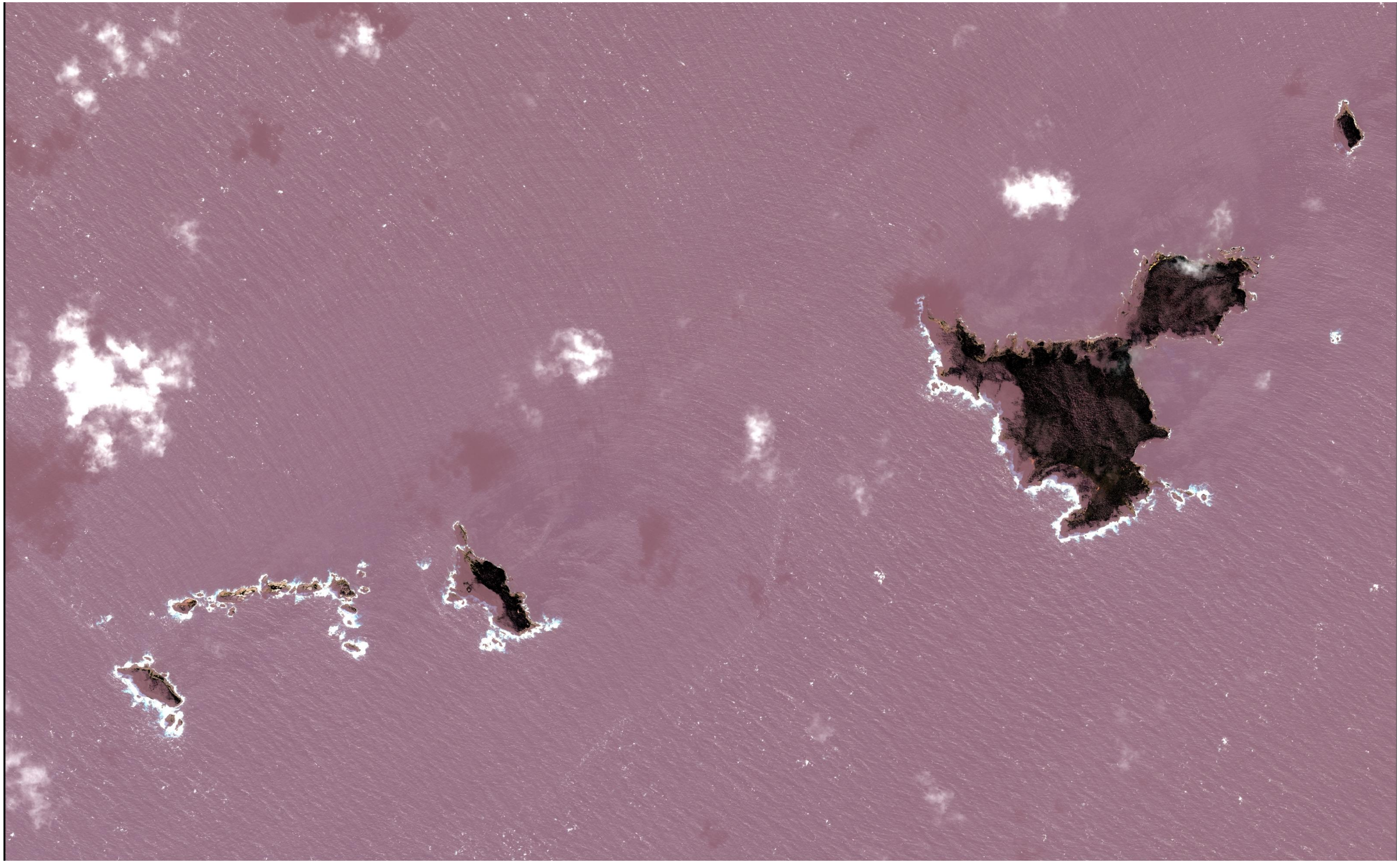
Appendix 1. 1. Three Kings Islands WorldView-2 colour image (04/04/2011)



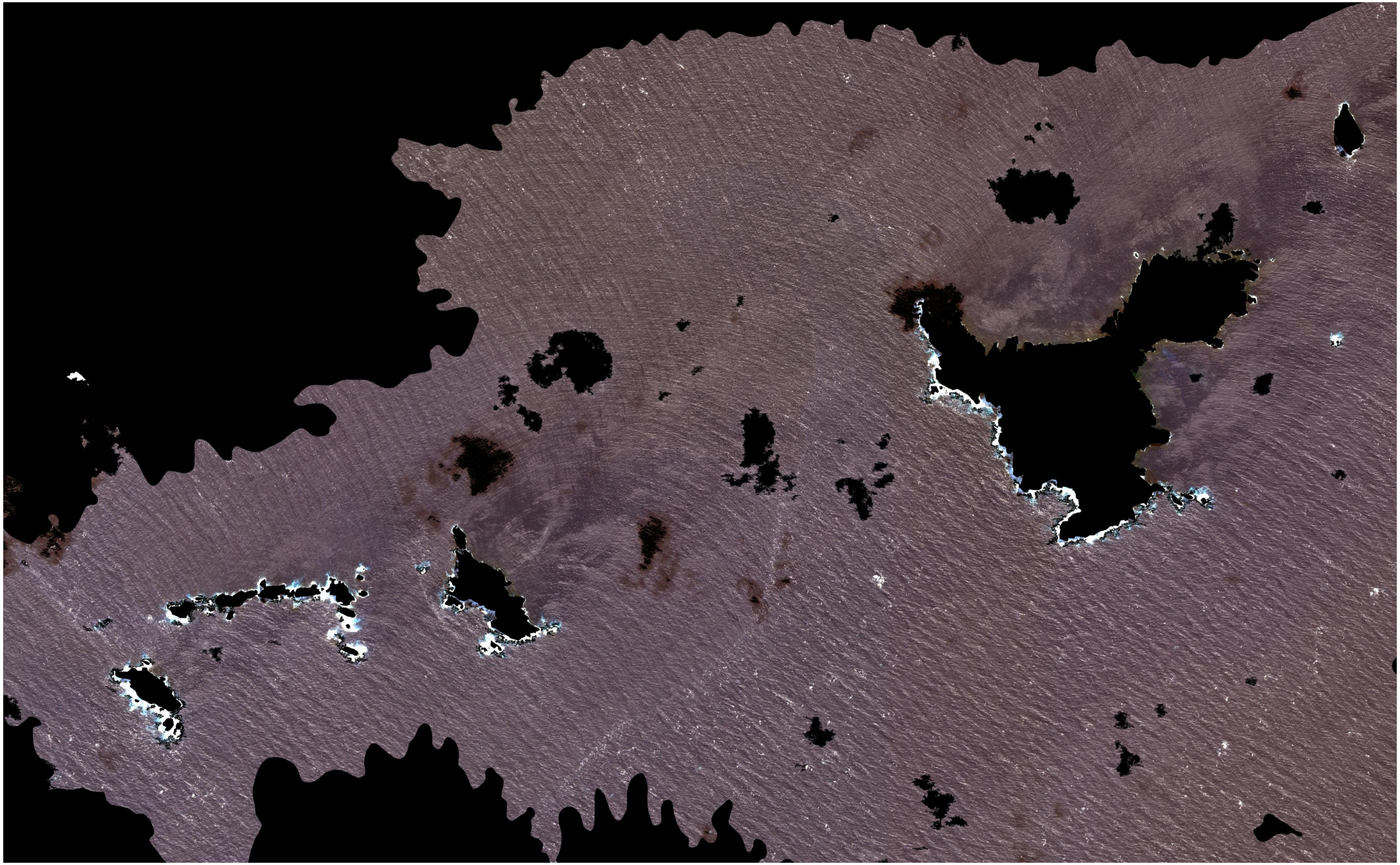
Appendix 1. 1. Radiance of Three Kings Islands



Appendix 1. 3. Deglinted image of Three Kings Islands

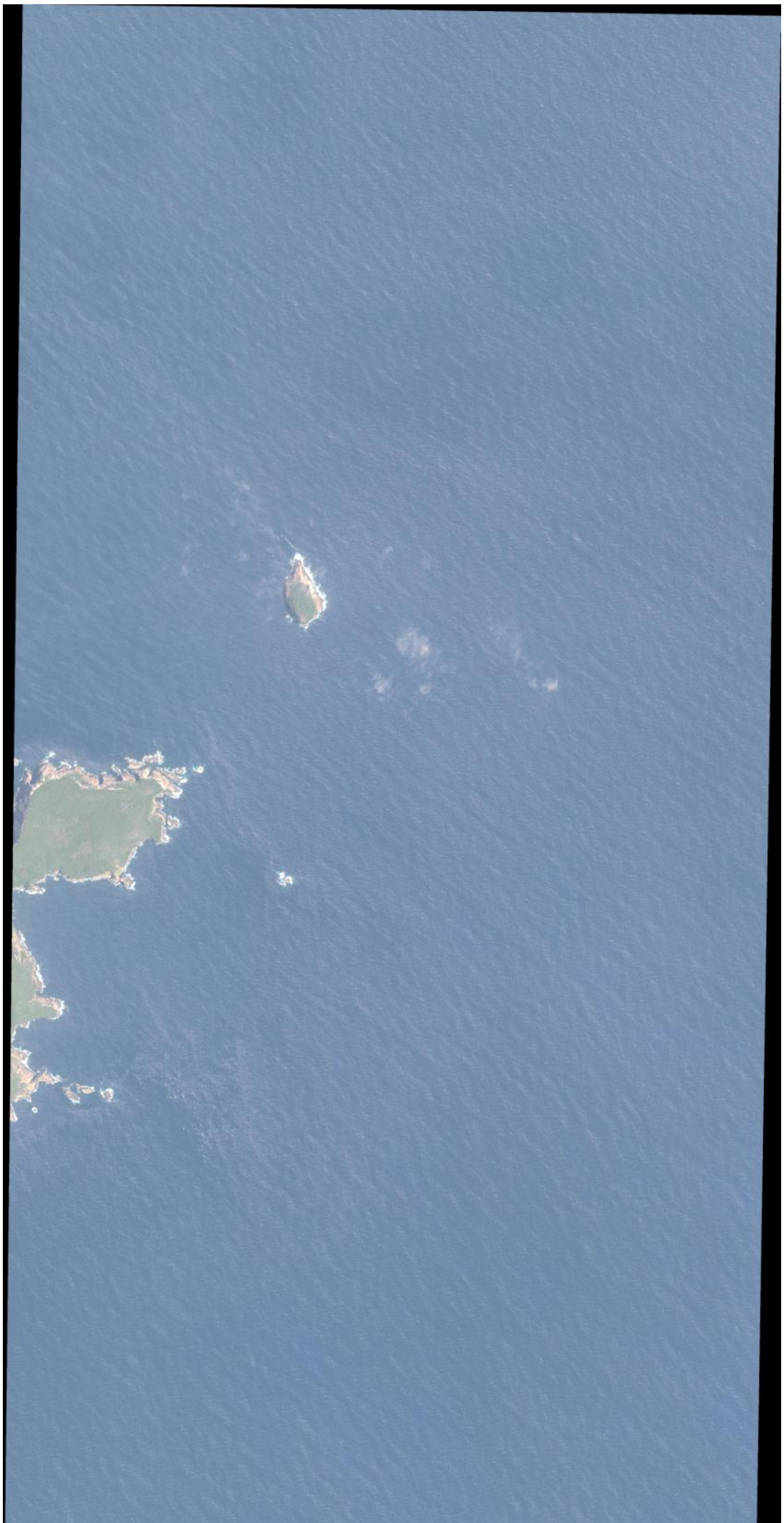


Appendix 1. 4. Mask of deglinted image Three Kings Islands



Appendix 1. 5. Land with clouds masked out

Appendix 1. 6. Original image (28/01/2010)

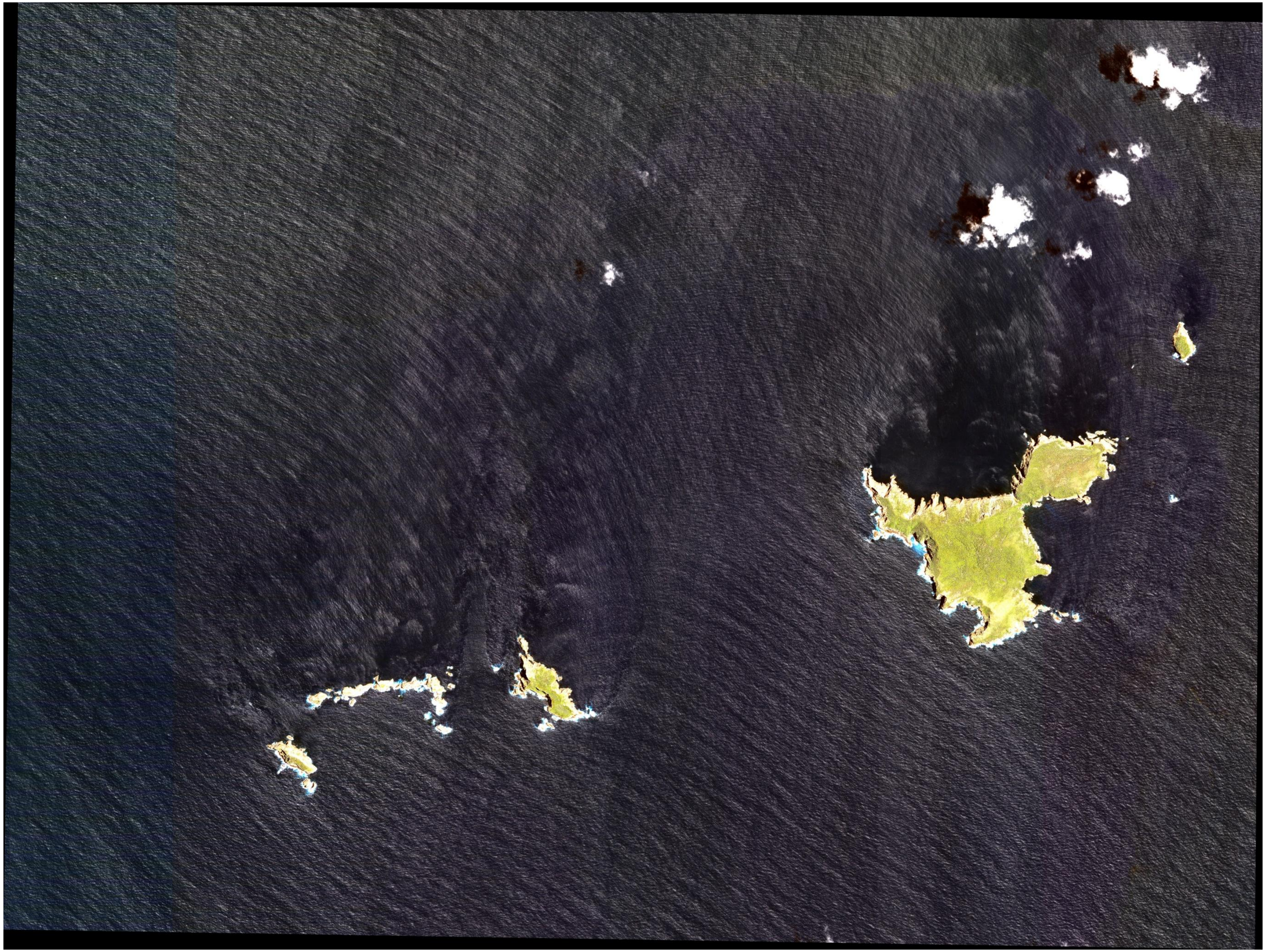


Appendix 1. 7. Radiance colour image of east of Three Kings Islands

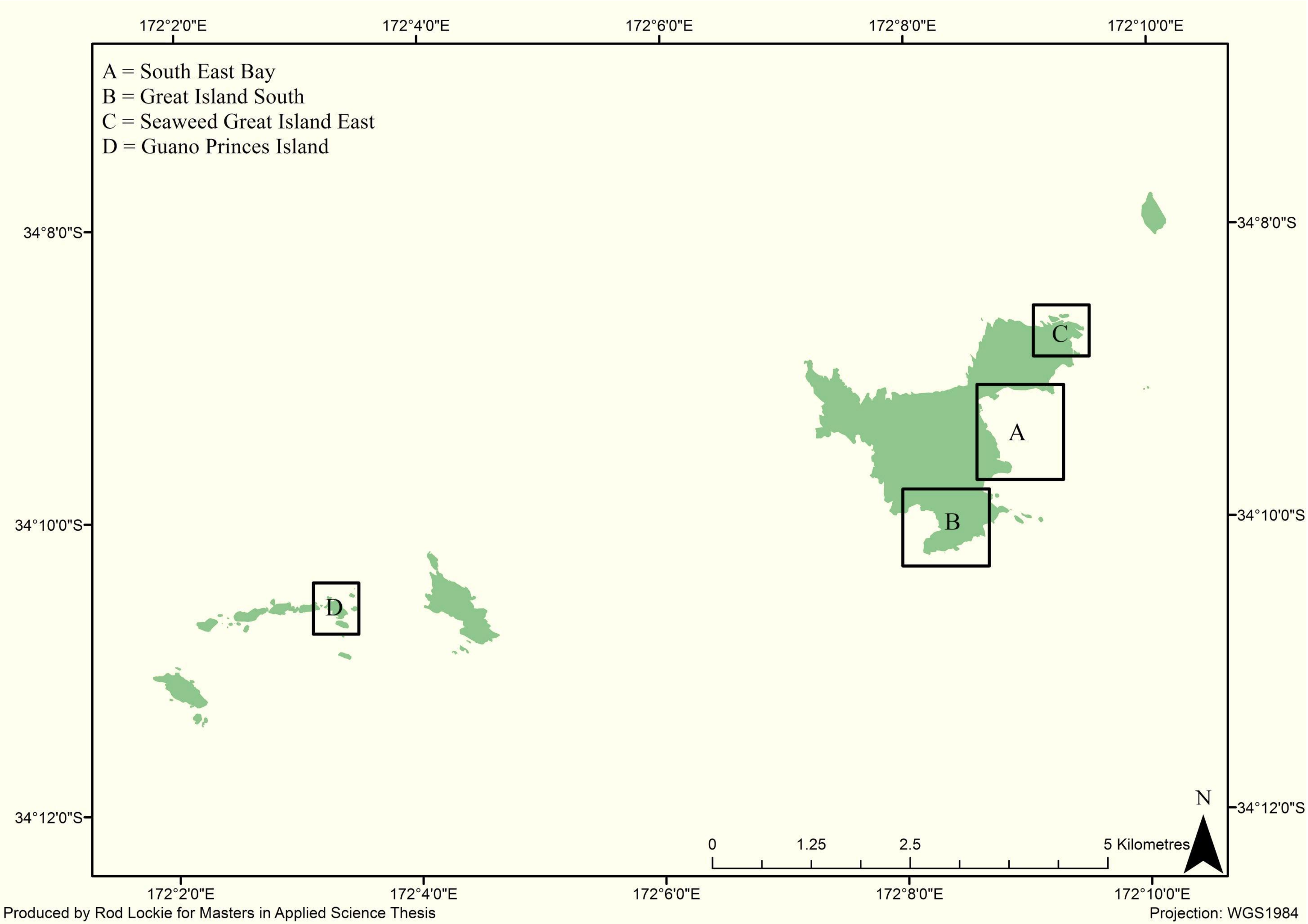
Appendix 1. 8. Deglinted image east of Three Kings Islands

Appendix 1. 9. Mask of deglinted image

Appendix 1. 10. ***Quickbird*** **colour image**

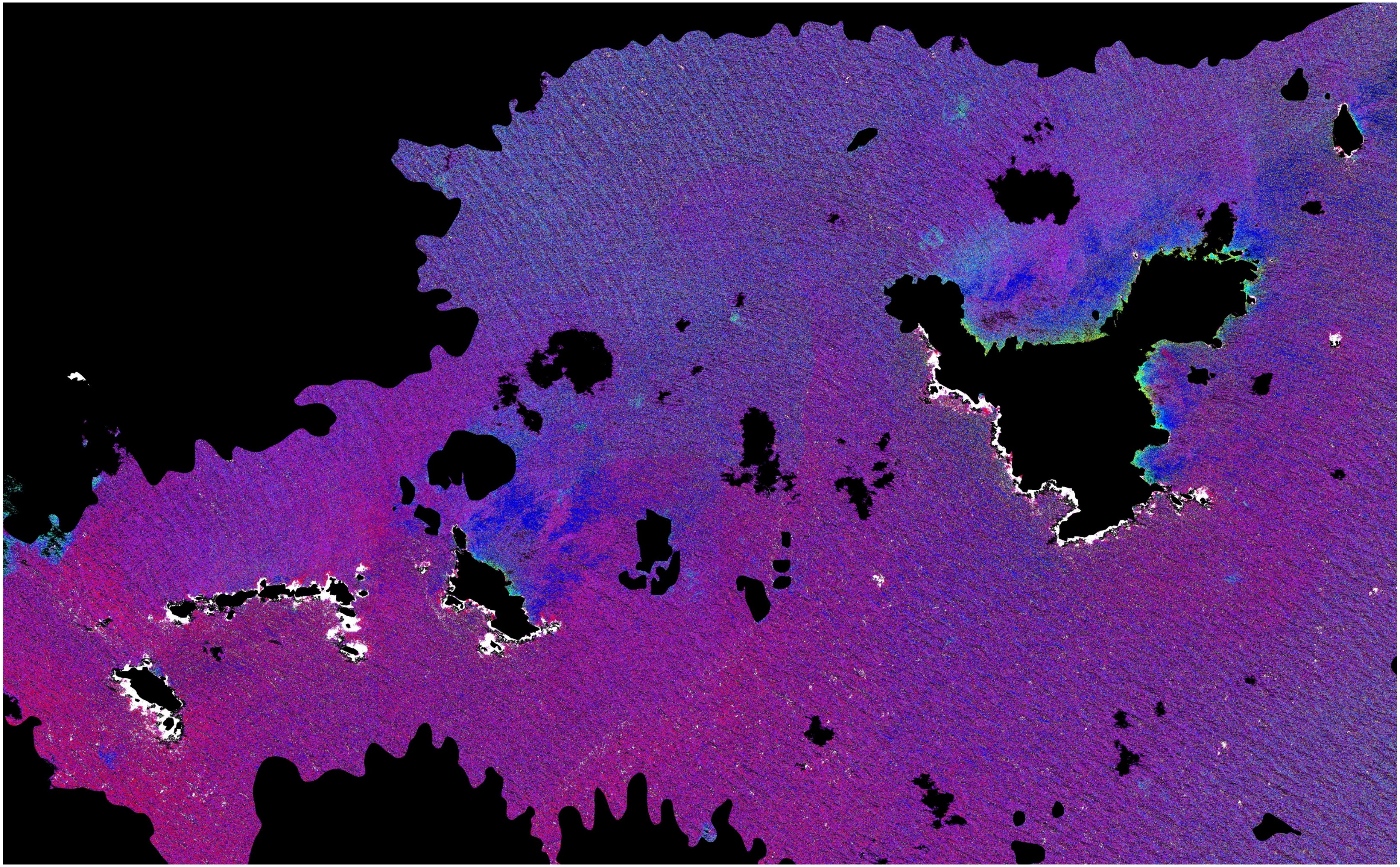


Appendix 1. 11. Subsets data that was used in Chapter 3 results

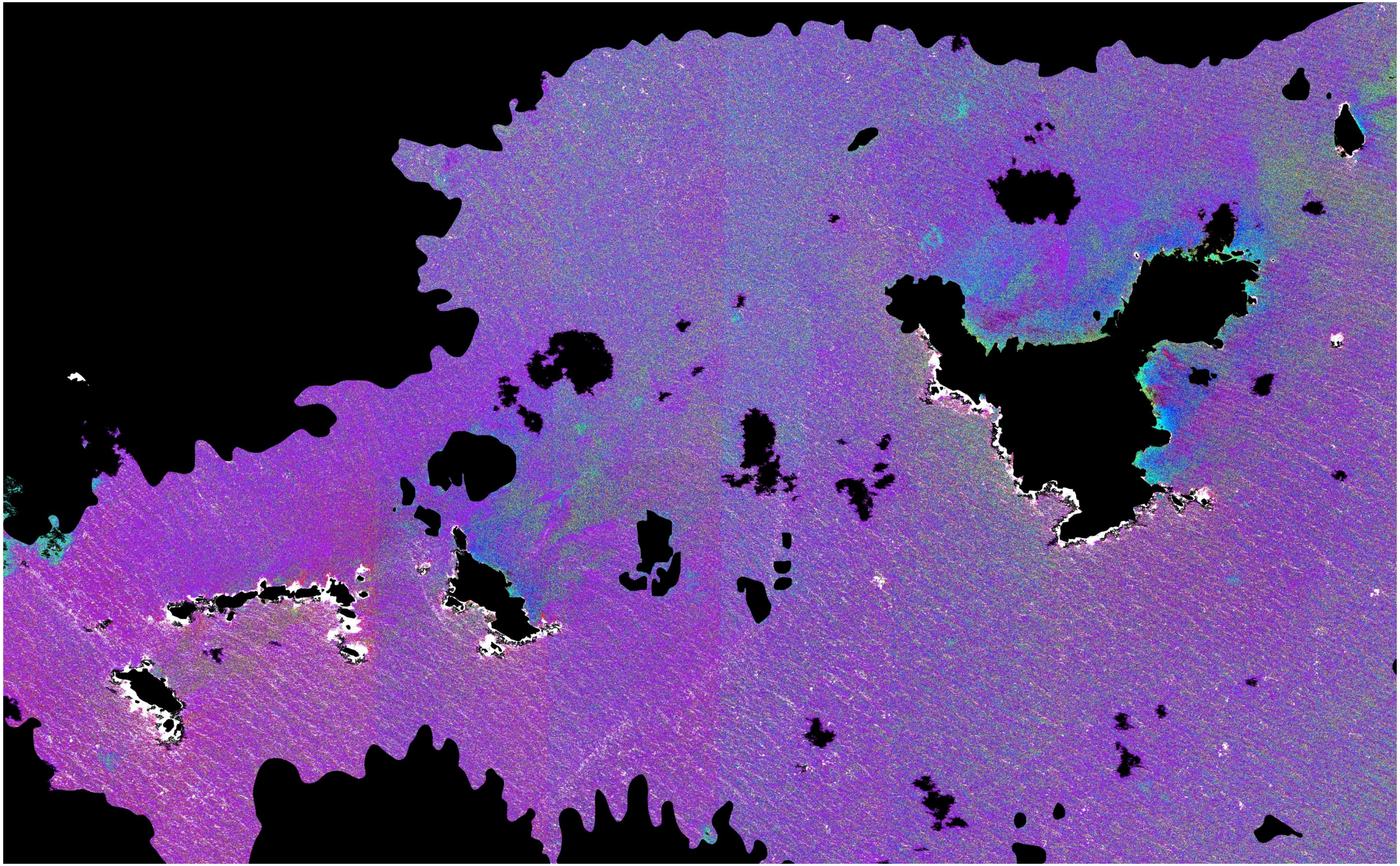


Appendix 2. Classifications

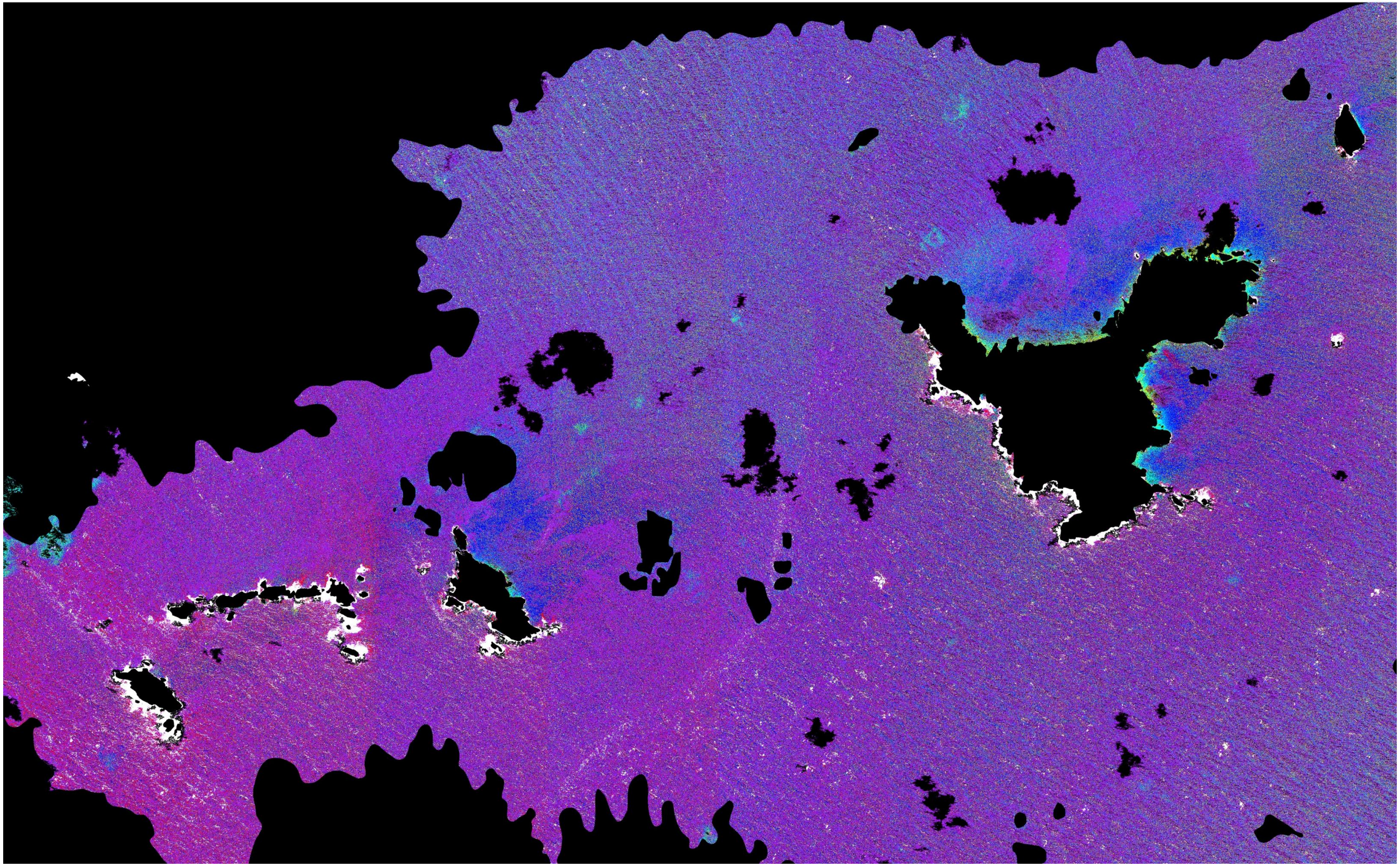
Appendix 2. 1. Minimum distance of marine classification (coastal, yellow, red-edge and NIR2)



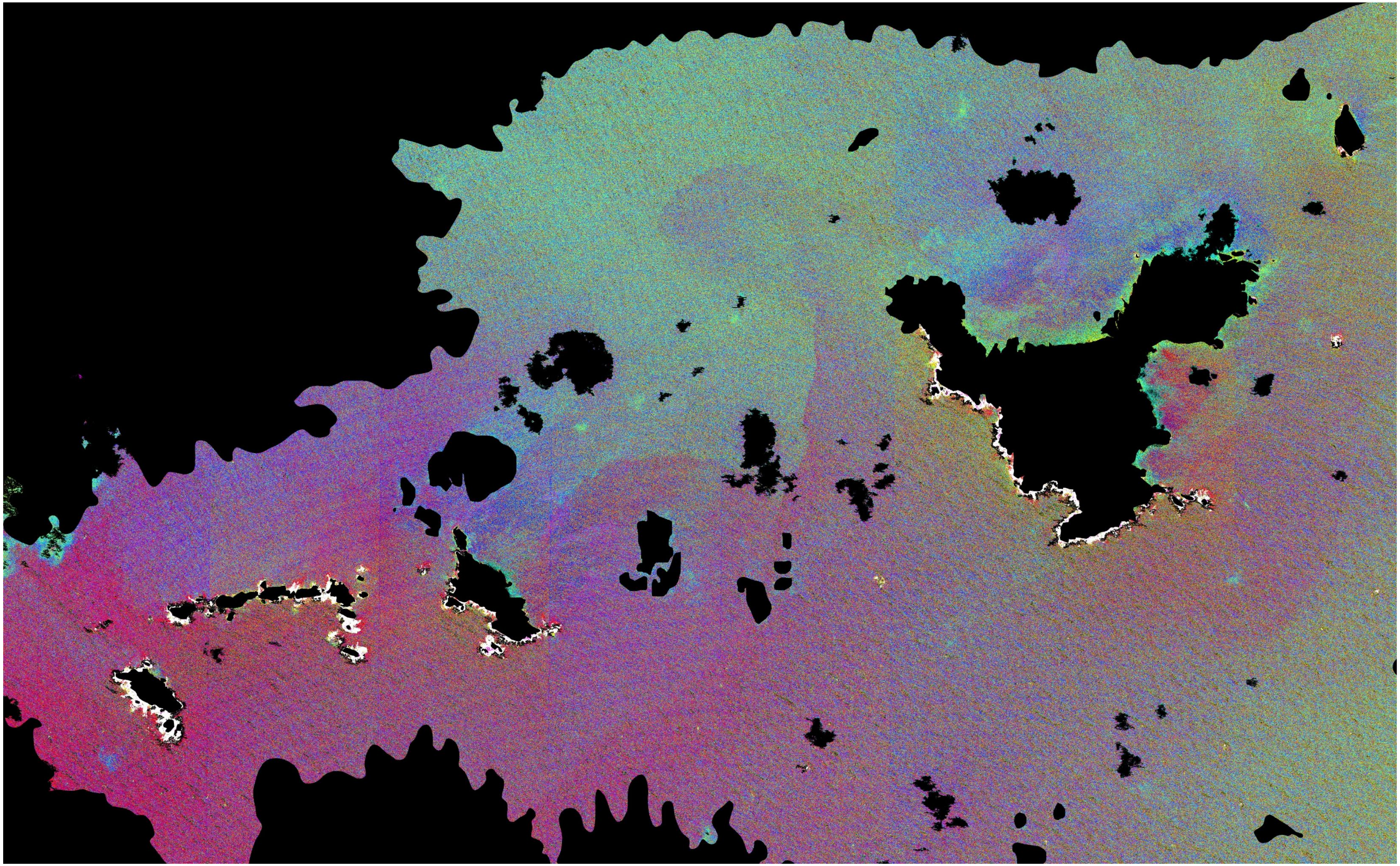
Appendix 2. 2. Minimum distance of marine classification (red, green, blue and NIR)



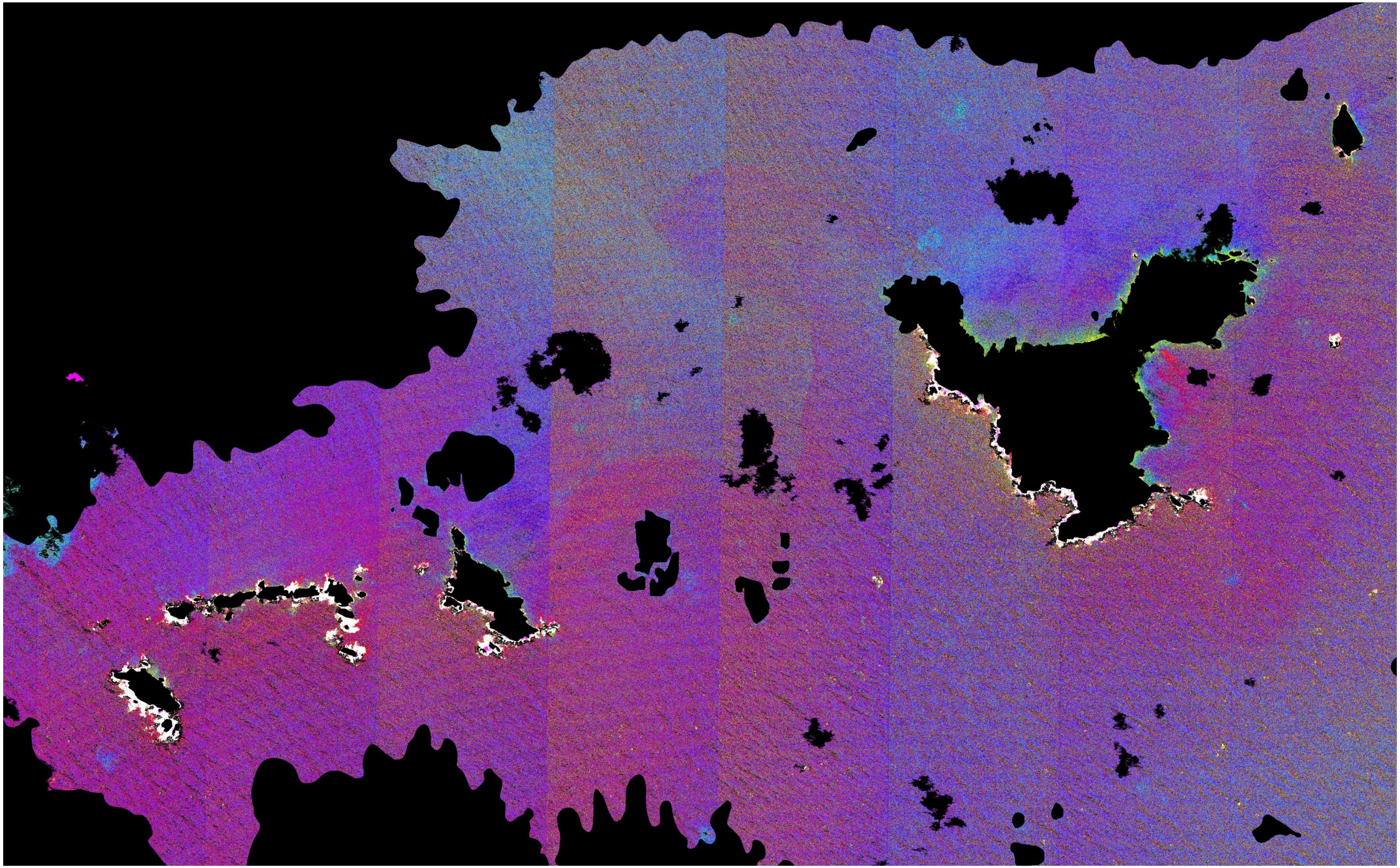
Appendix 2. 3. Minimum distance of marine classification (all *WorldView-2* bands)



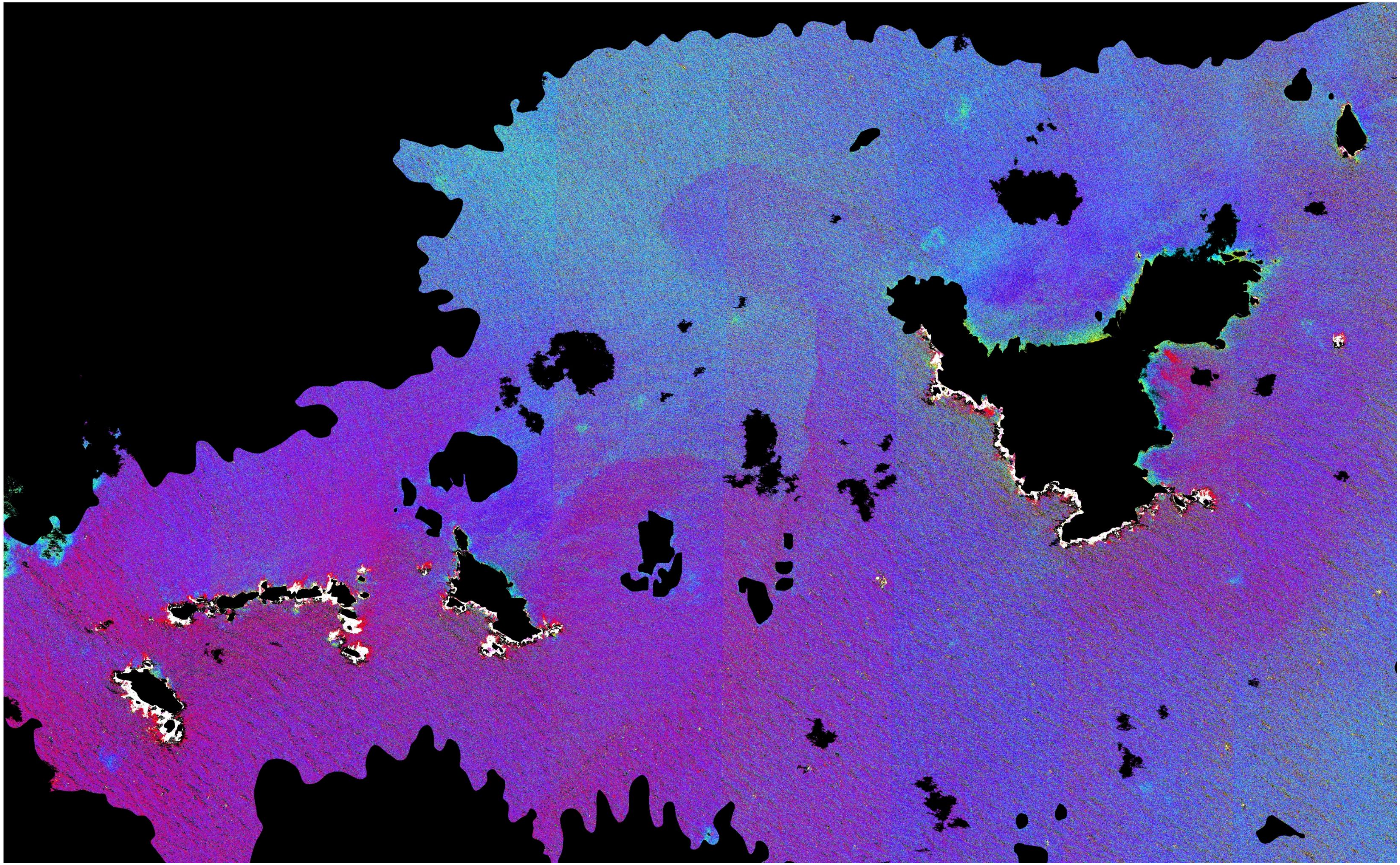
Appendix 2. 4. Mahalanobis distance of marine classification (coastal, yellow, red-edge and NIR2)



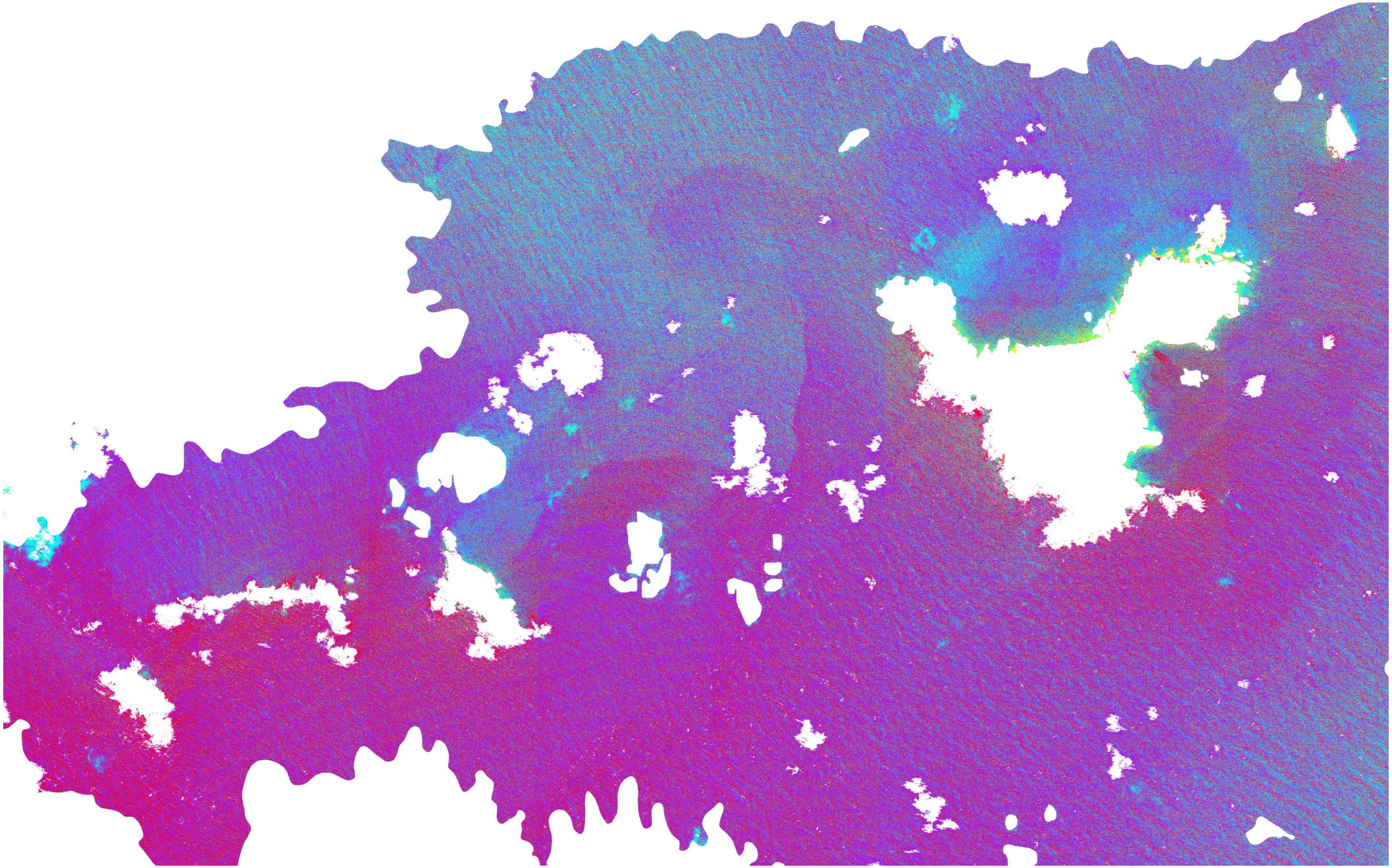
Appendix 2. 5. Mahalanobis distance of marine classification (red, green, blue and NIR)



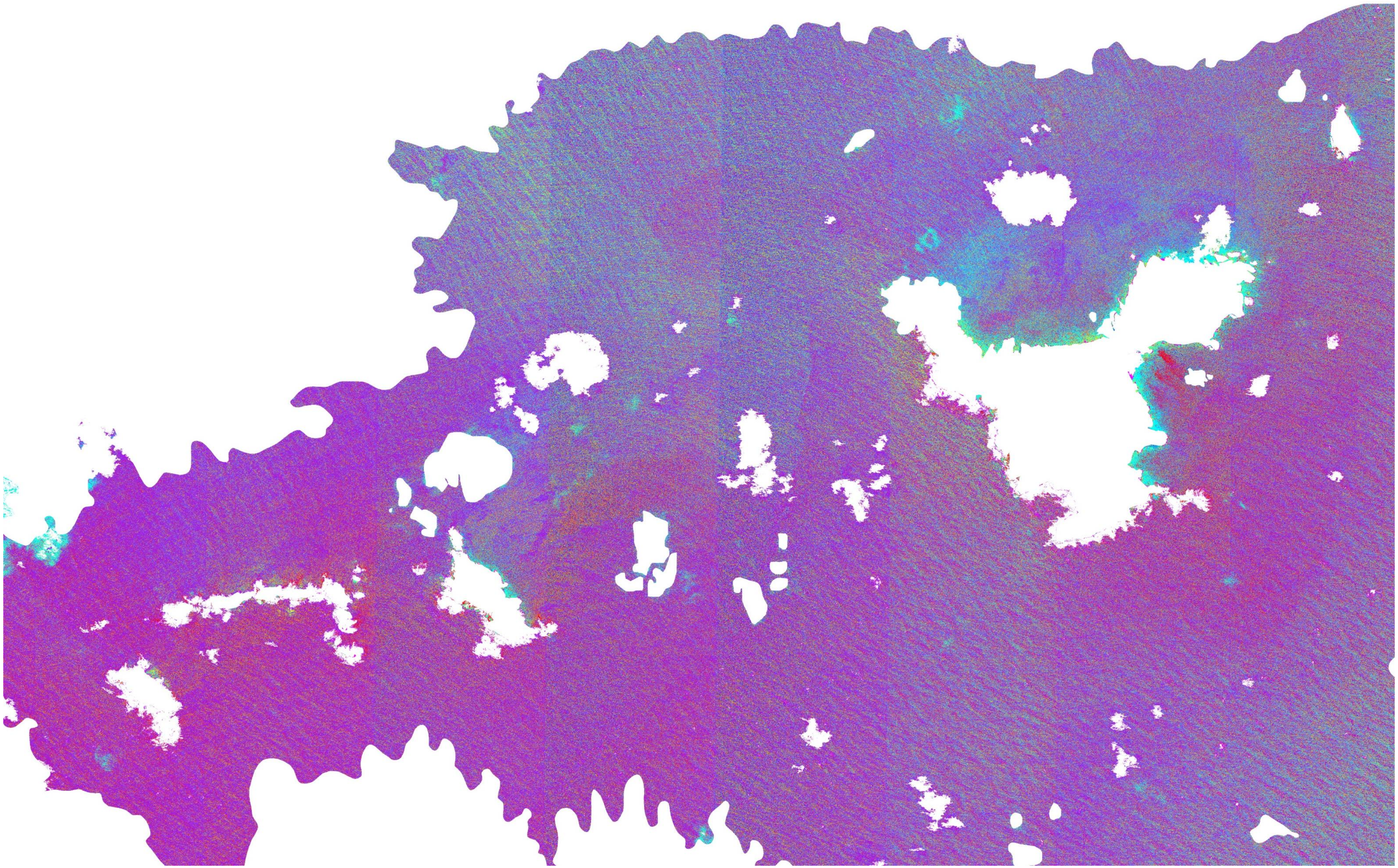
Appendix 2. 6. Mahalanobis distance of marine classification (all *WorldView-2* bands)



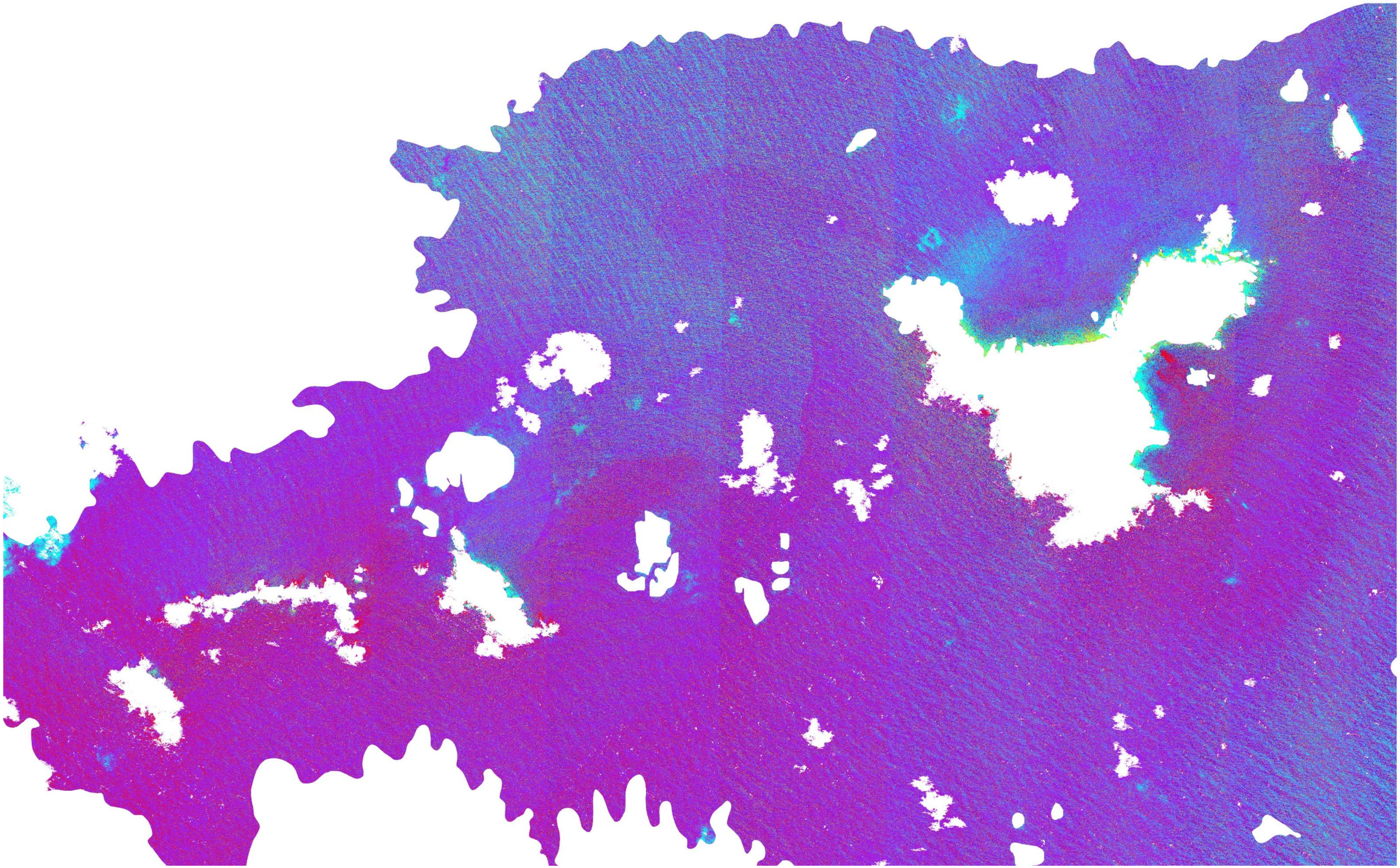
Appendix 2. 7. Maximum likelihood of marine classification (coastal, yellow, red-edge and NIR2)



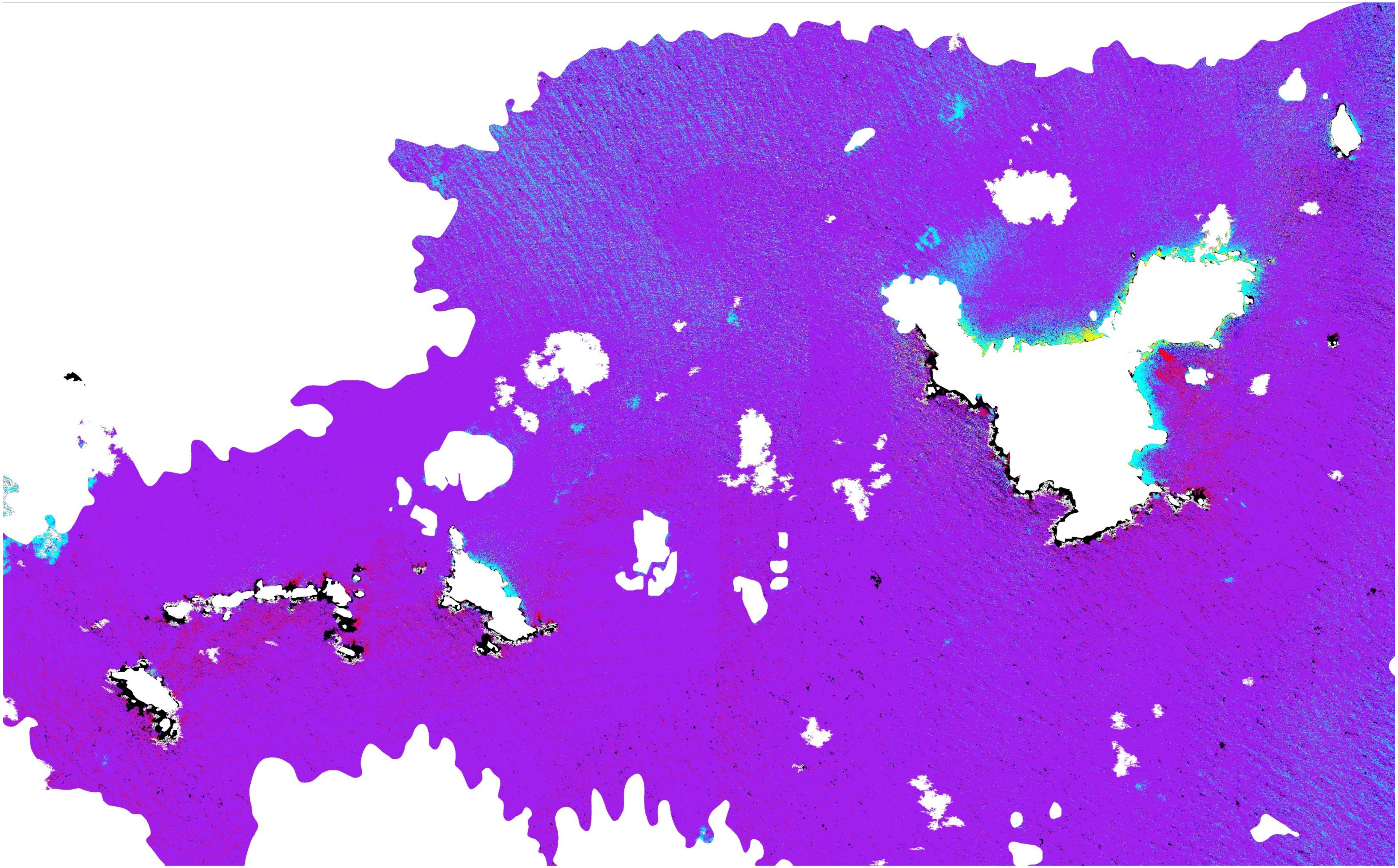
Appendix 2. 8. Maximum likelihood of marine classification (red, green, blue and NIR)



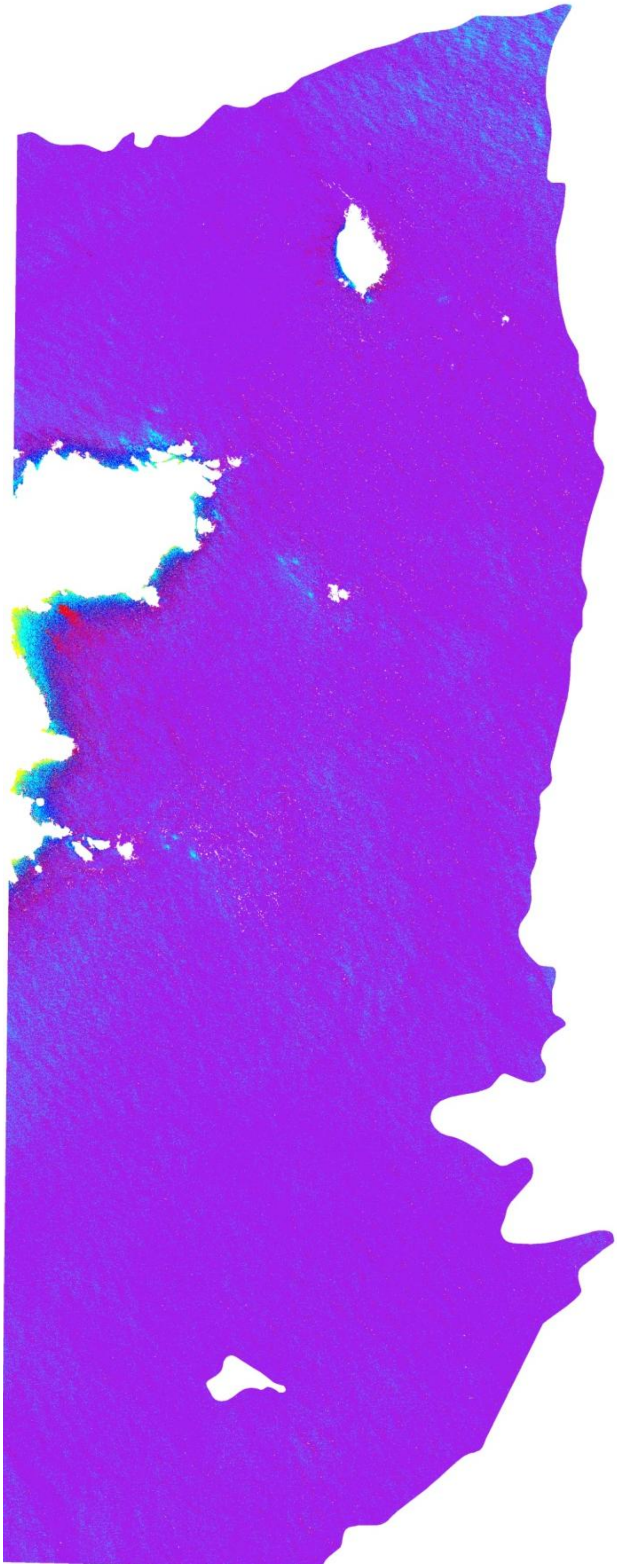
Appendix 2. 9. Maximum likelihood of marine classification (all *WorldView-2* bands)



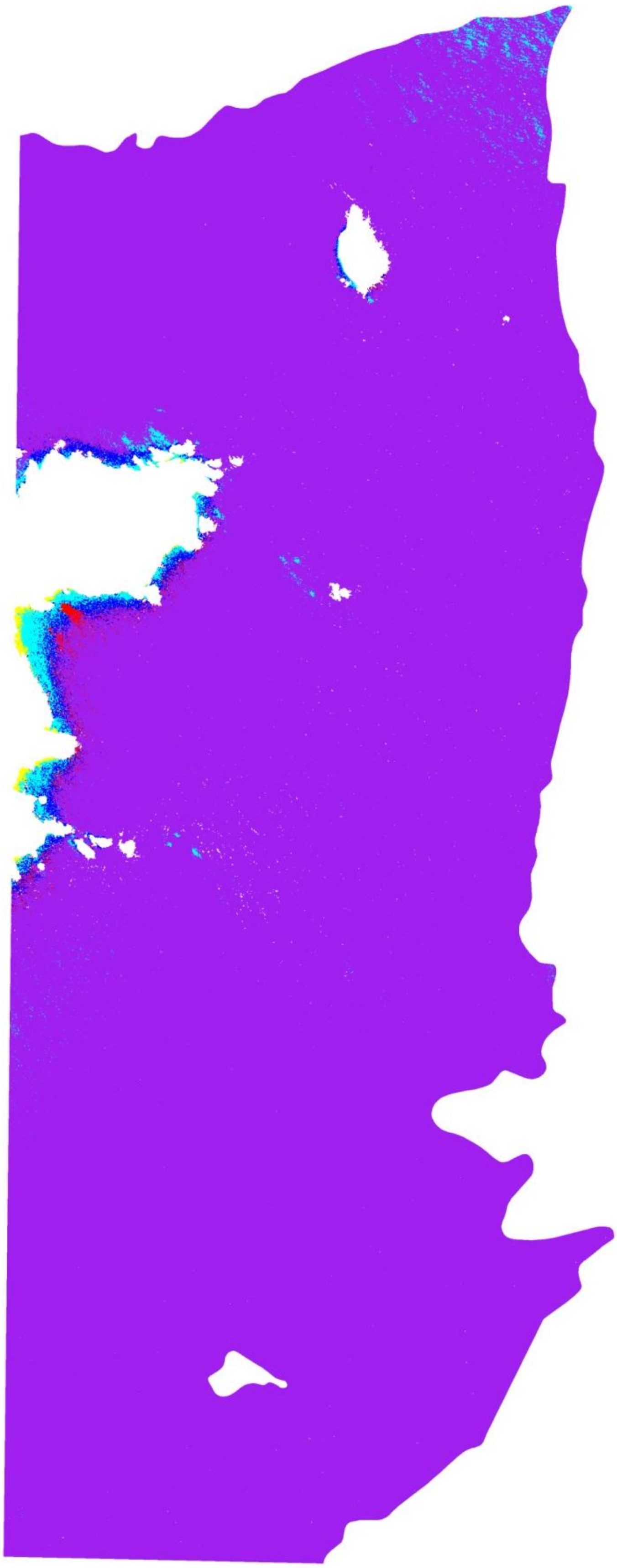
Appendix 2. 10. Majority analysis of maximum likelihood from marine classification (all *WorldView-2* bands)



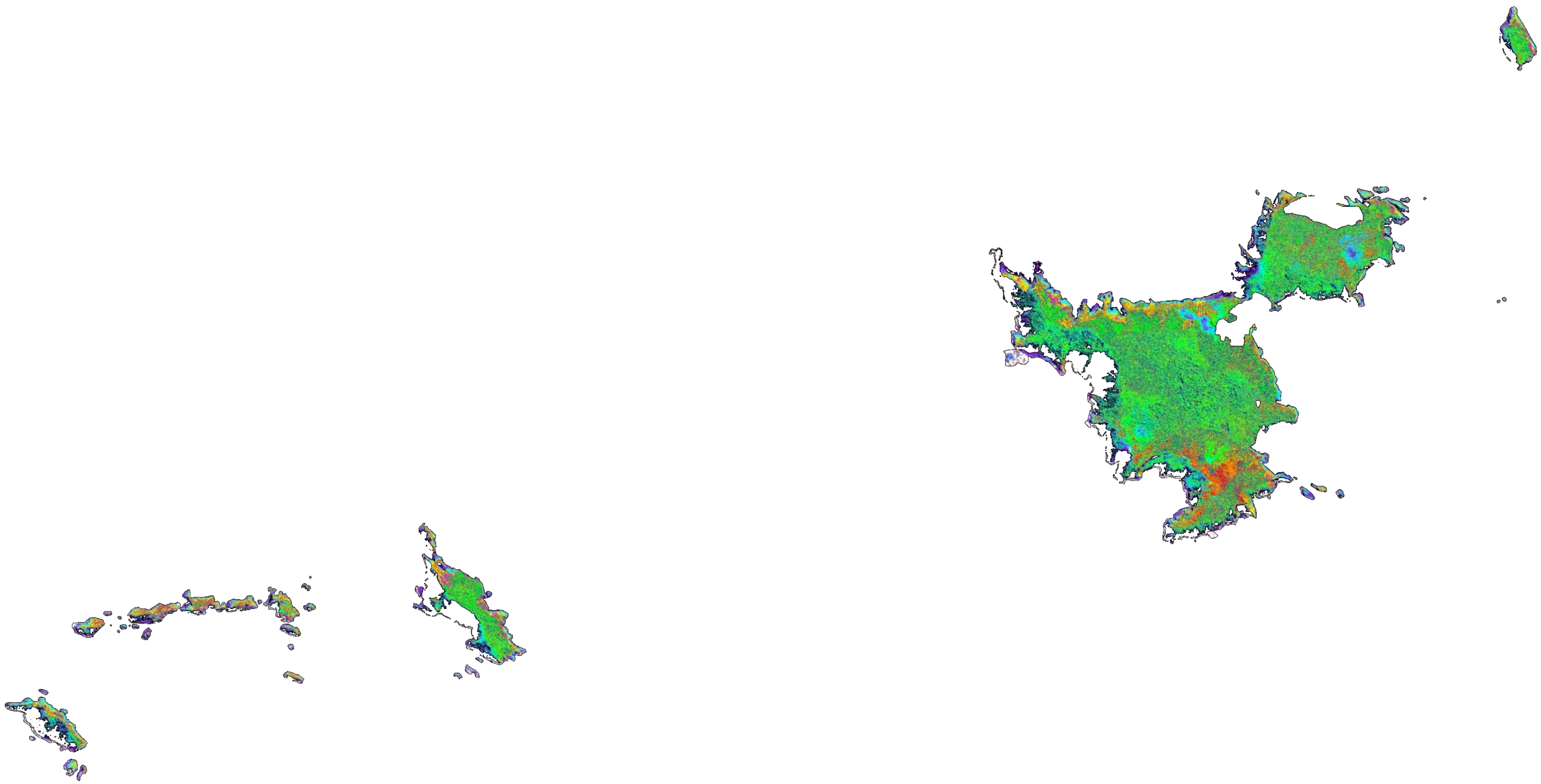
Appendix 2. 11. Maximum likelihood of east Three Kings Islands. (all *WorldView-2* bands)



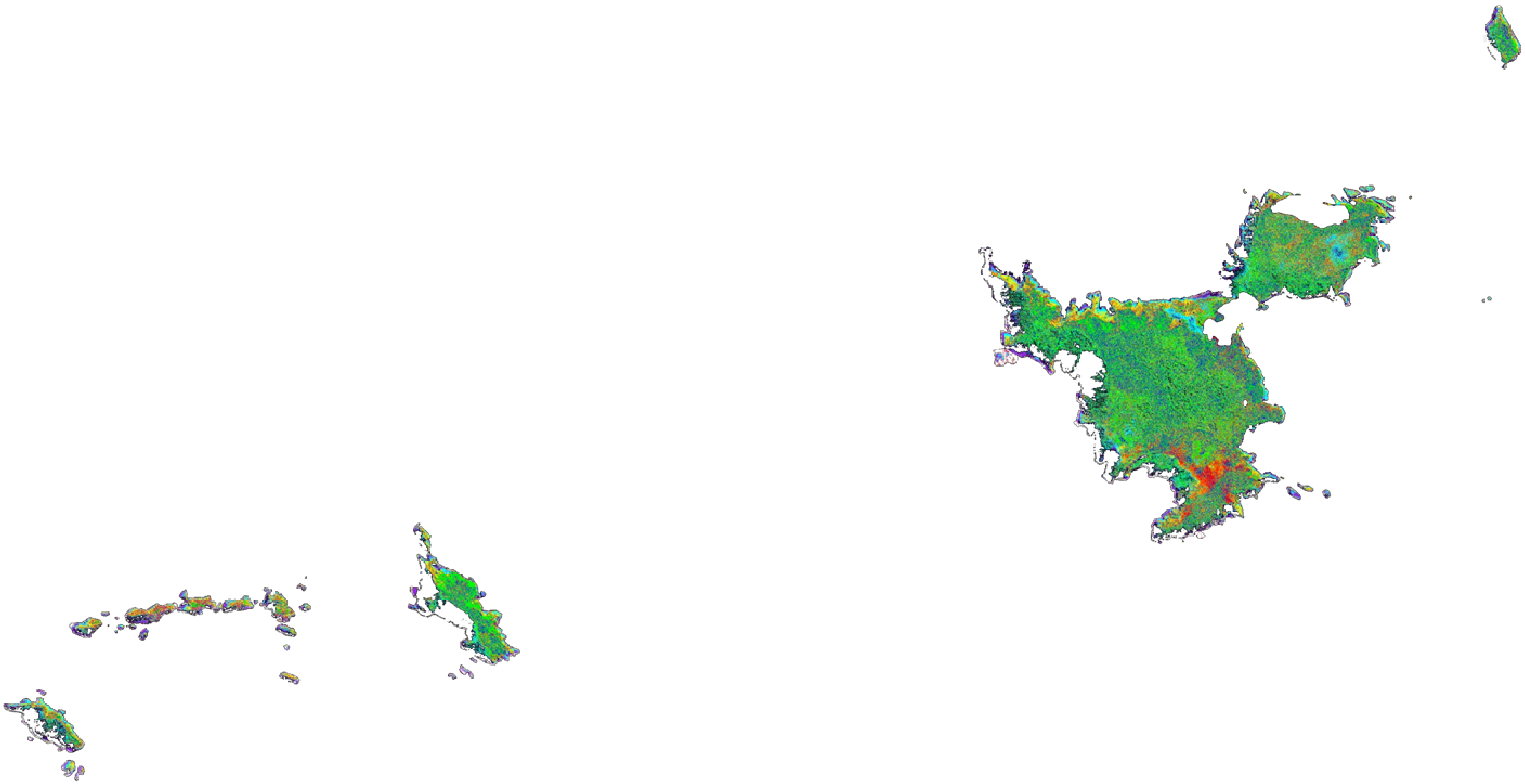
Appendix 2. 12. Majority analysis of maximum likelihood east Three Kings Islands. (all WorldView-2 bands)



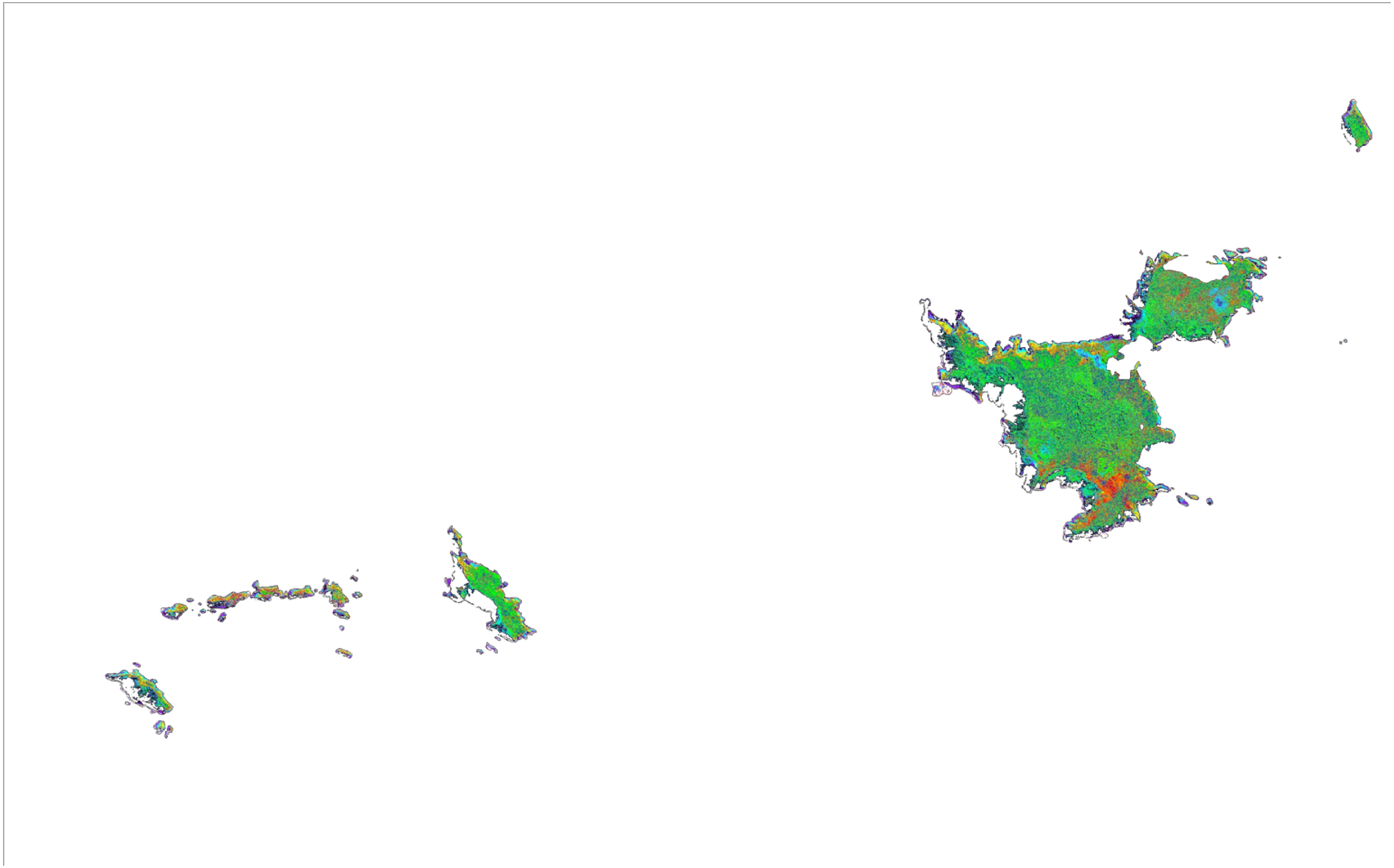
Appendix 2. 13. Minimum distance of terrestrial classification (coastal, yellow, red-edge and NIR2)



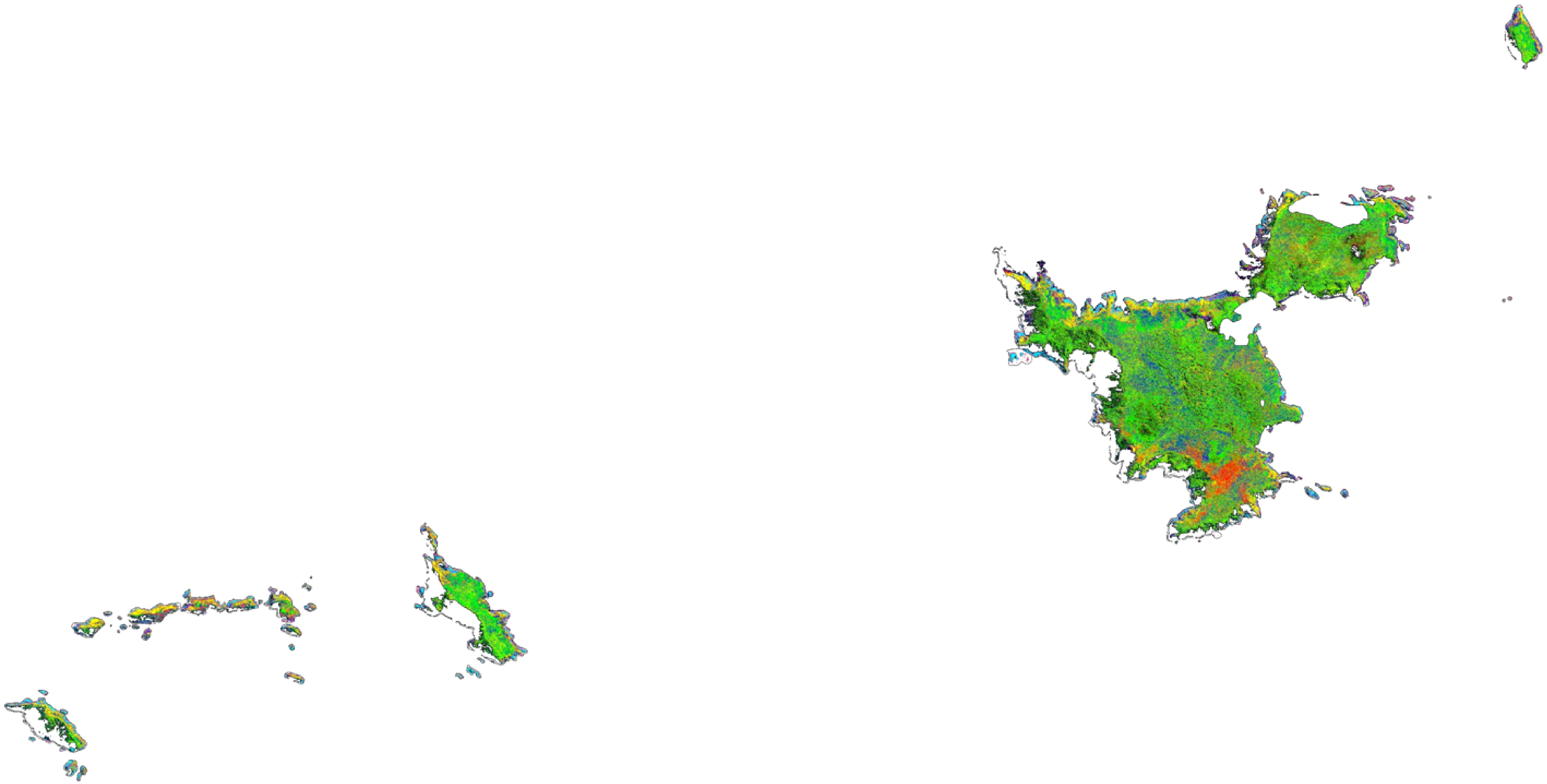
Appendix 2. 14. Minimum distance of terrestrial classification (red, green, blue and NIR)



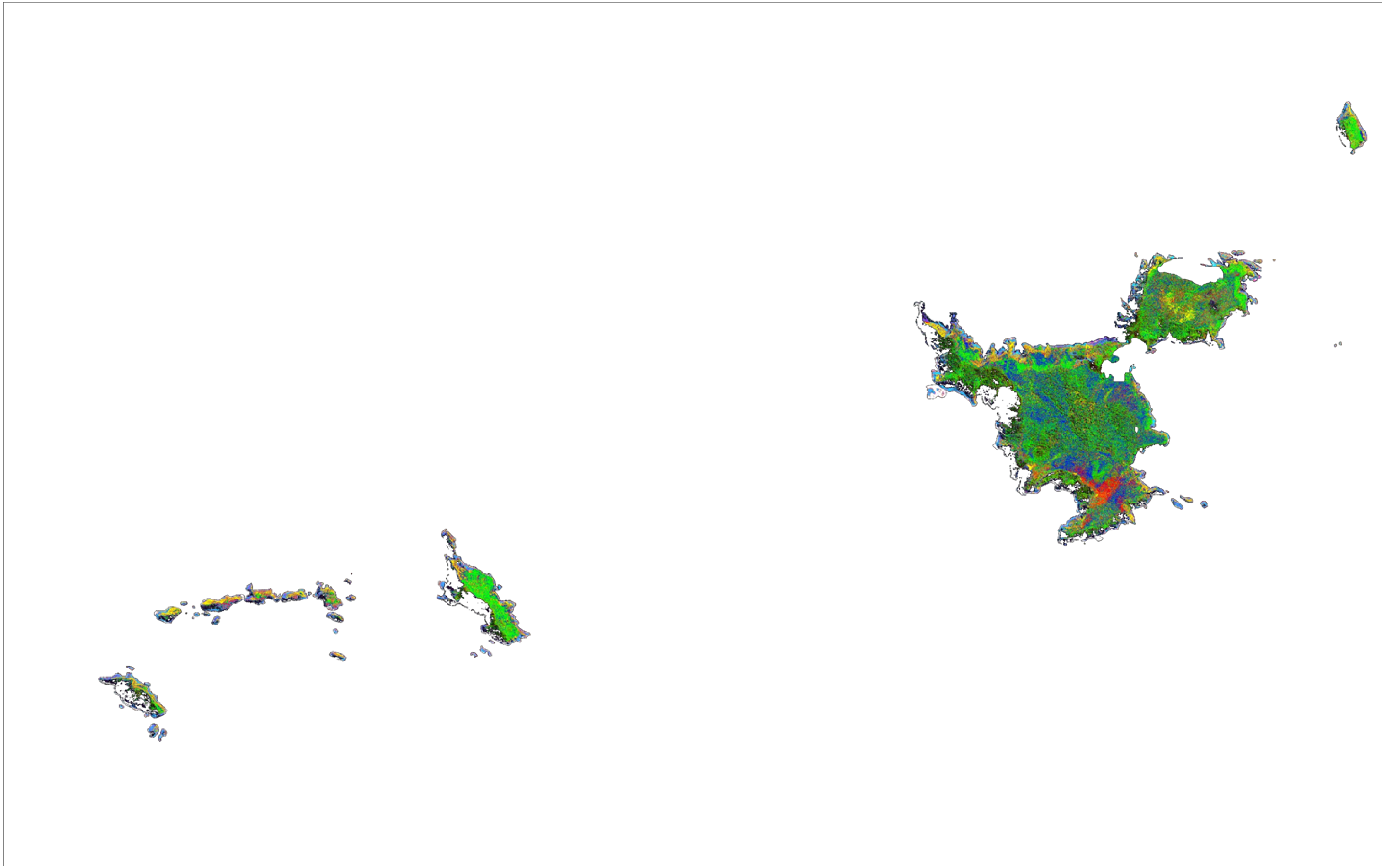
Appendix 2. 15. Minimum distance of terrestrial classification (all *WorldView-2* bands)



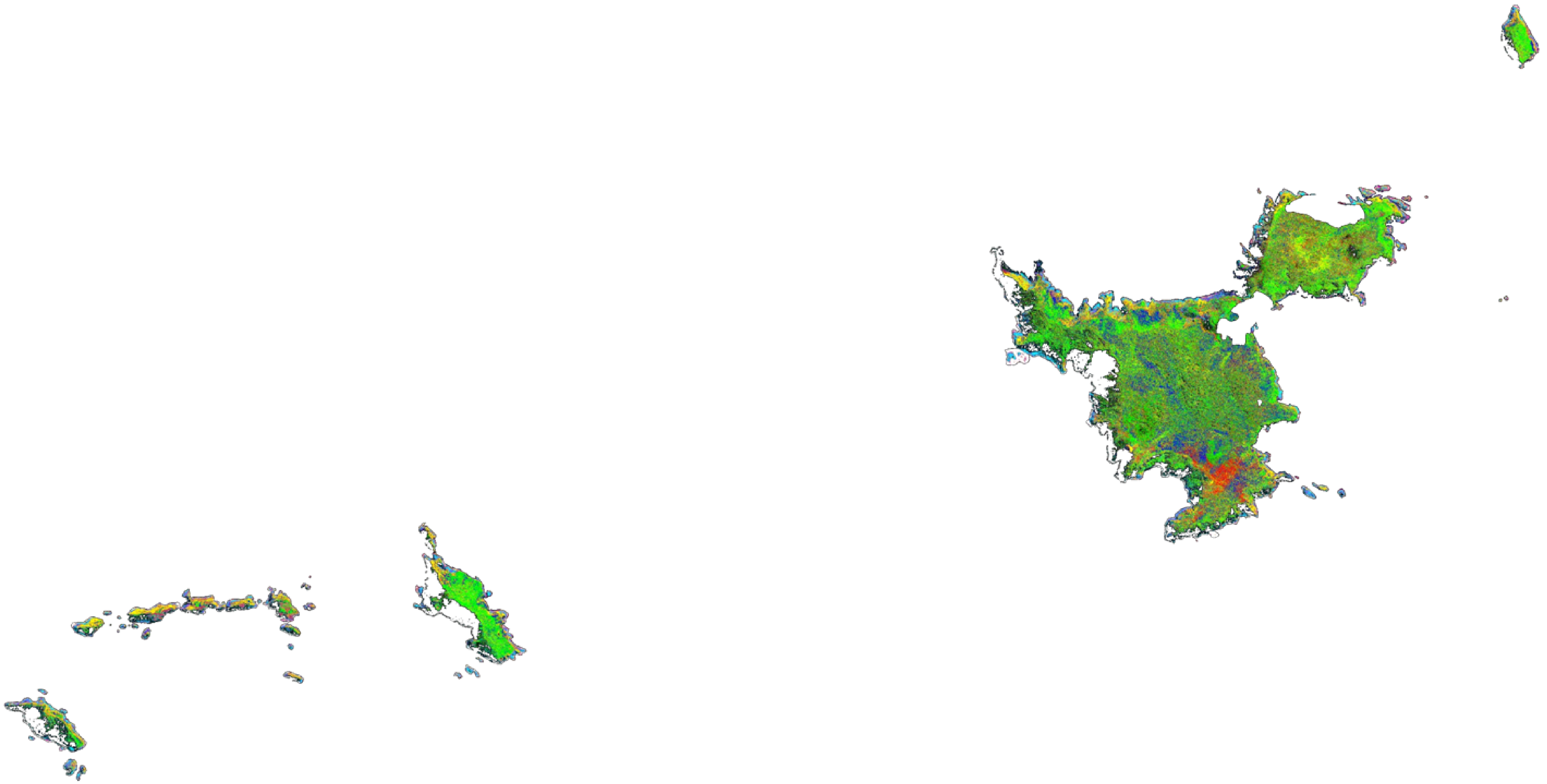
Appendix 2. 16. Mahalanobis distance of terrestrial classification (coastal, yellow, red-edge and NIR2)



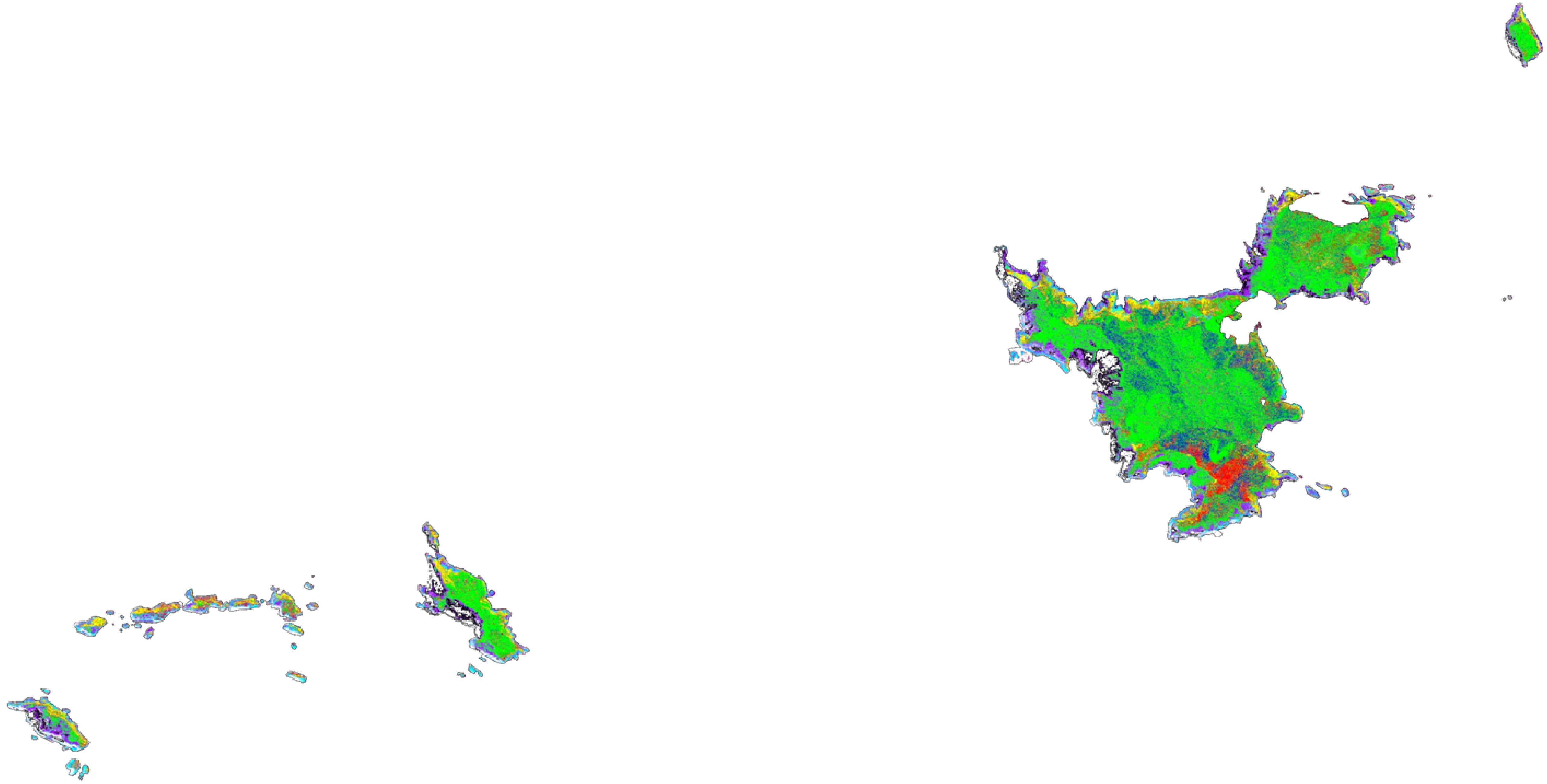
Appendix 2. 17. Mahalanobis distance of terrestrial classification (red, green, blue and NIR)



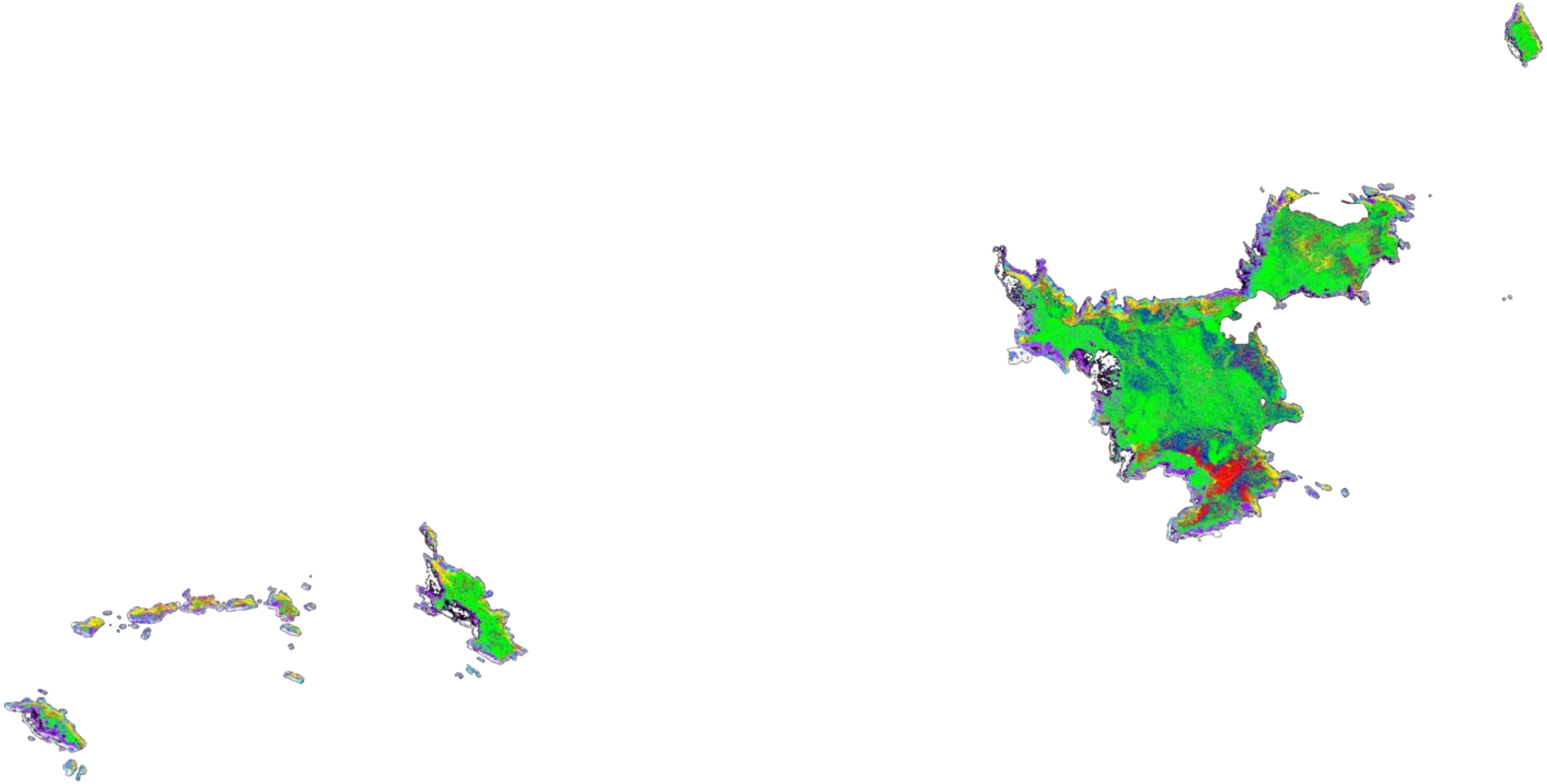
Appendix 2. 18. Mahalanobis distance of terrestrial classification (all *WorldView-2* bands)



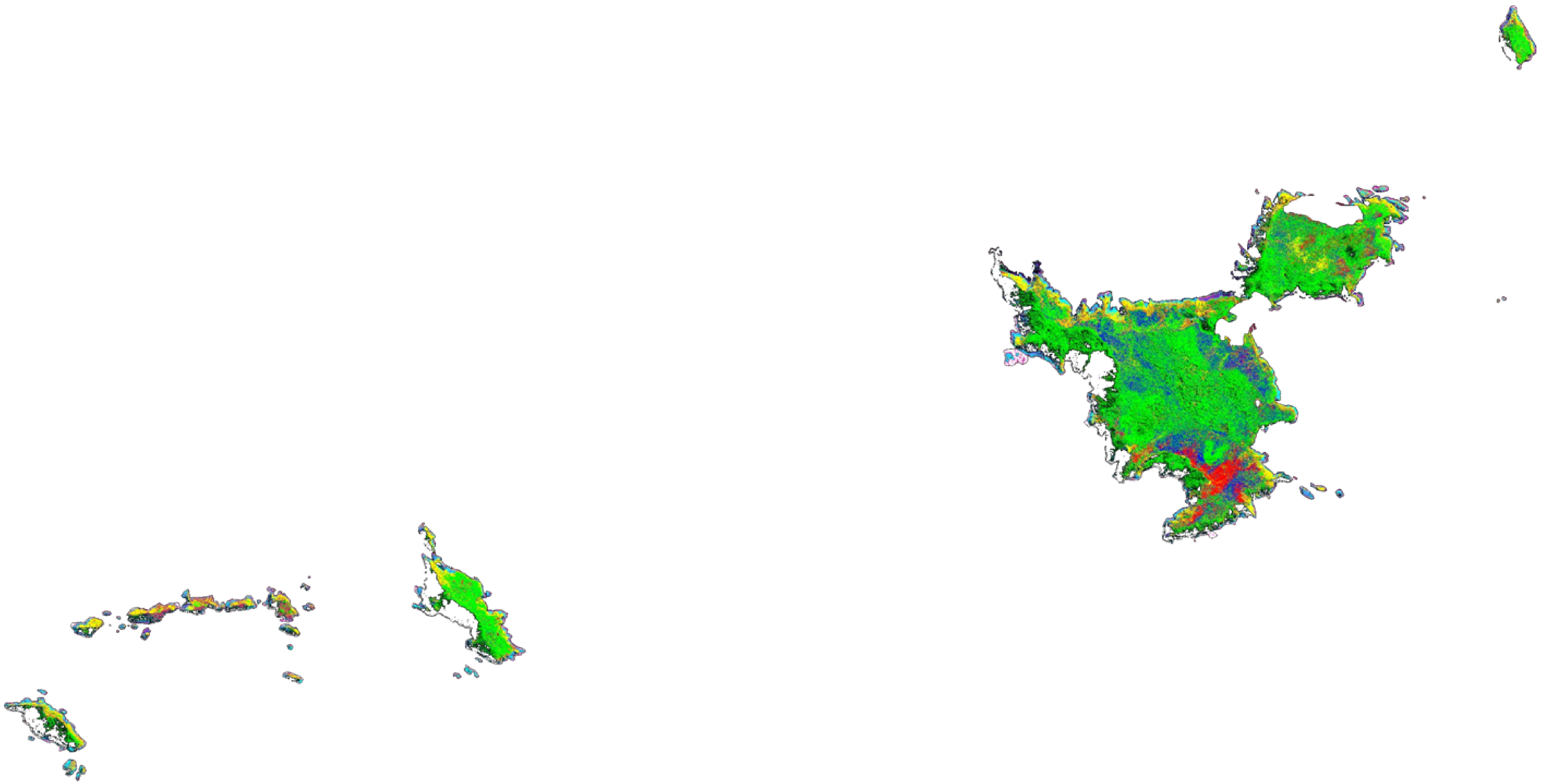
Appendix 2. 19. Maximum likelihood of terrestrial classification (coastal, yellow, red-edge and NIR2)



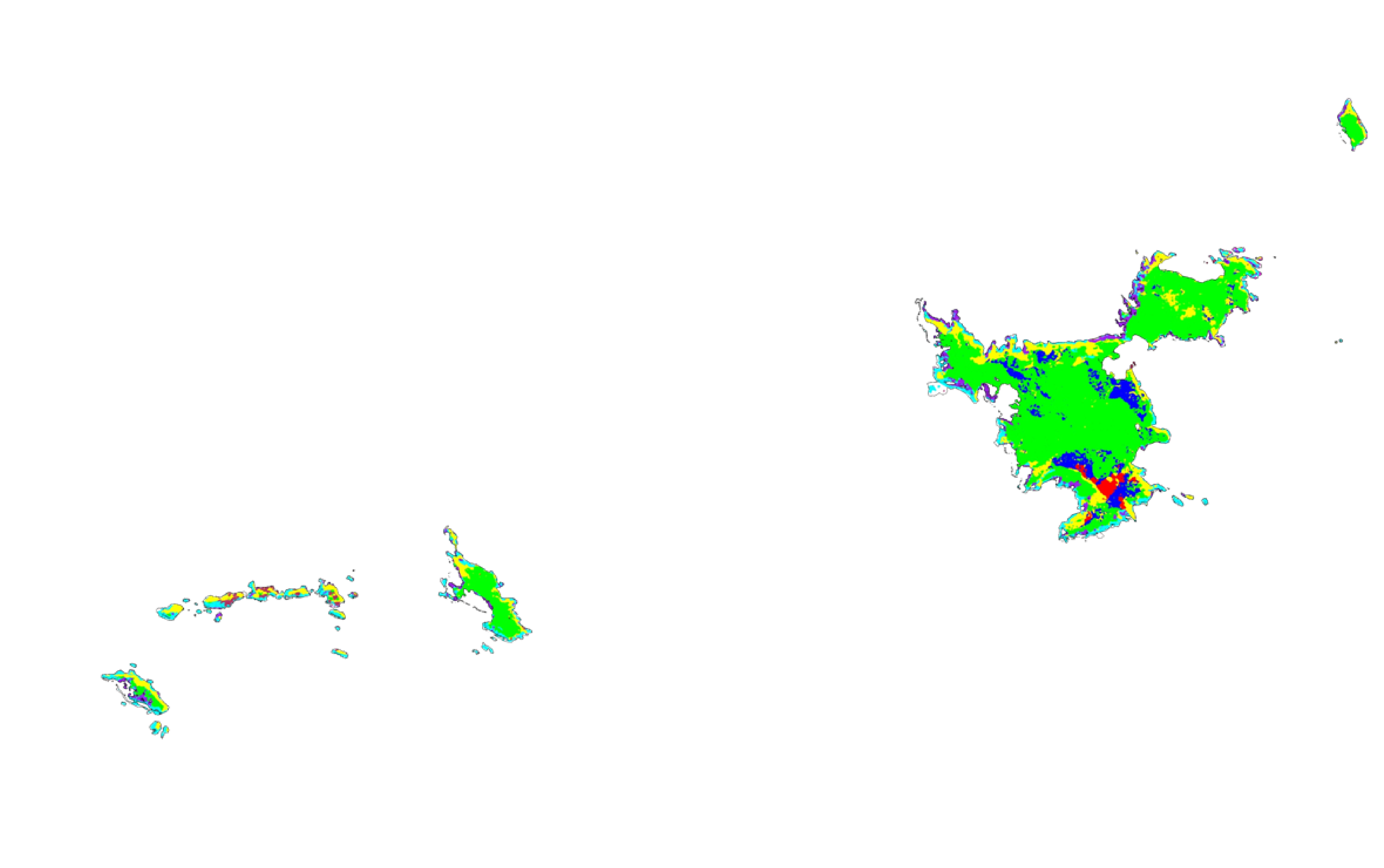
Appendix 2. 20. Maximum likelihood of terrestrial classification (Red, green, blue and NIR)



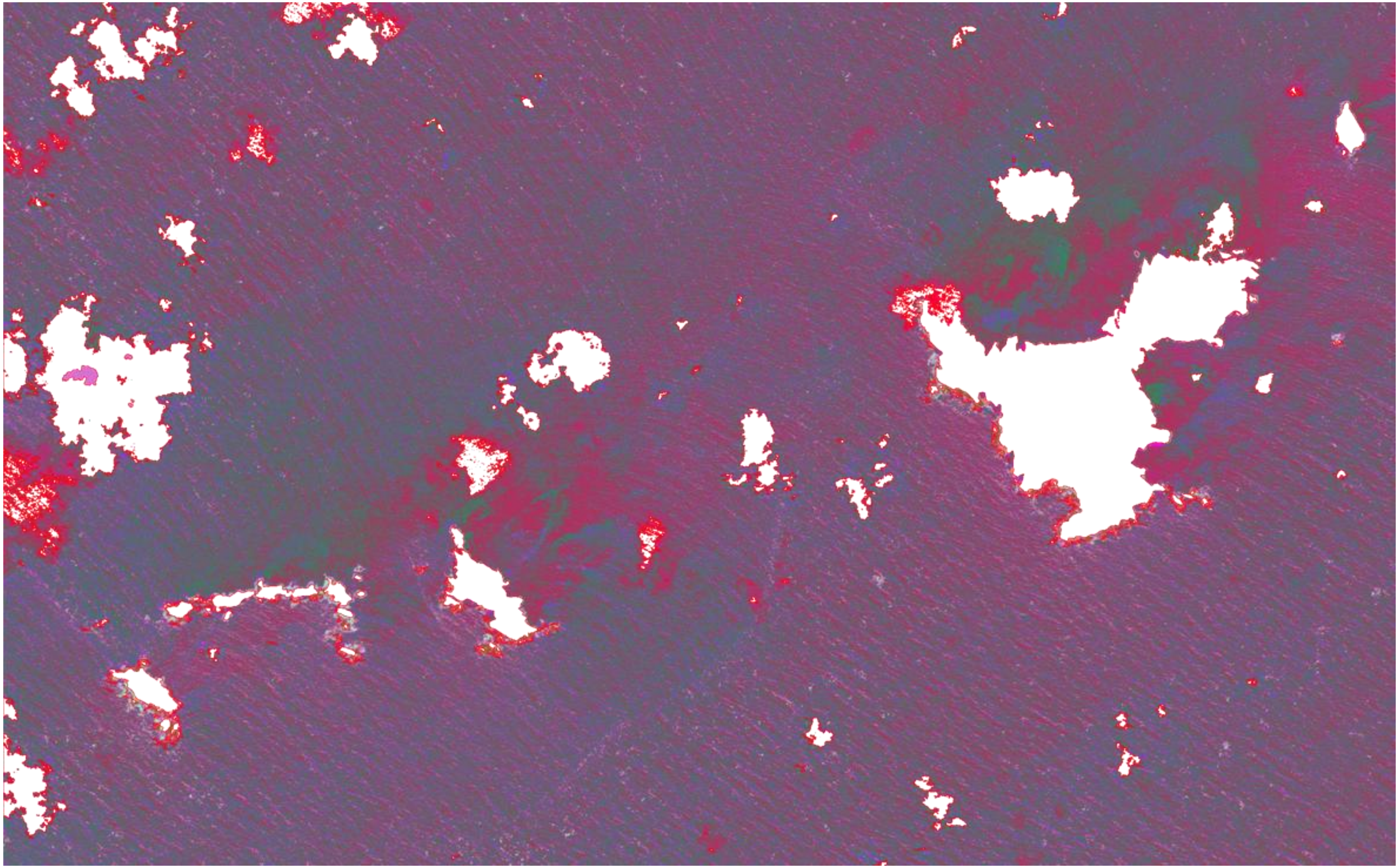
Appendix 2. 21. Maximum likelihood of terrestrial classification (all *WorldView-2* bands)



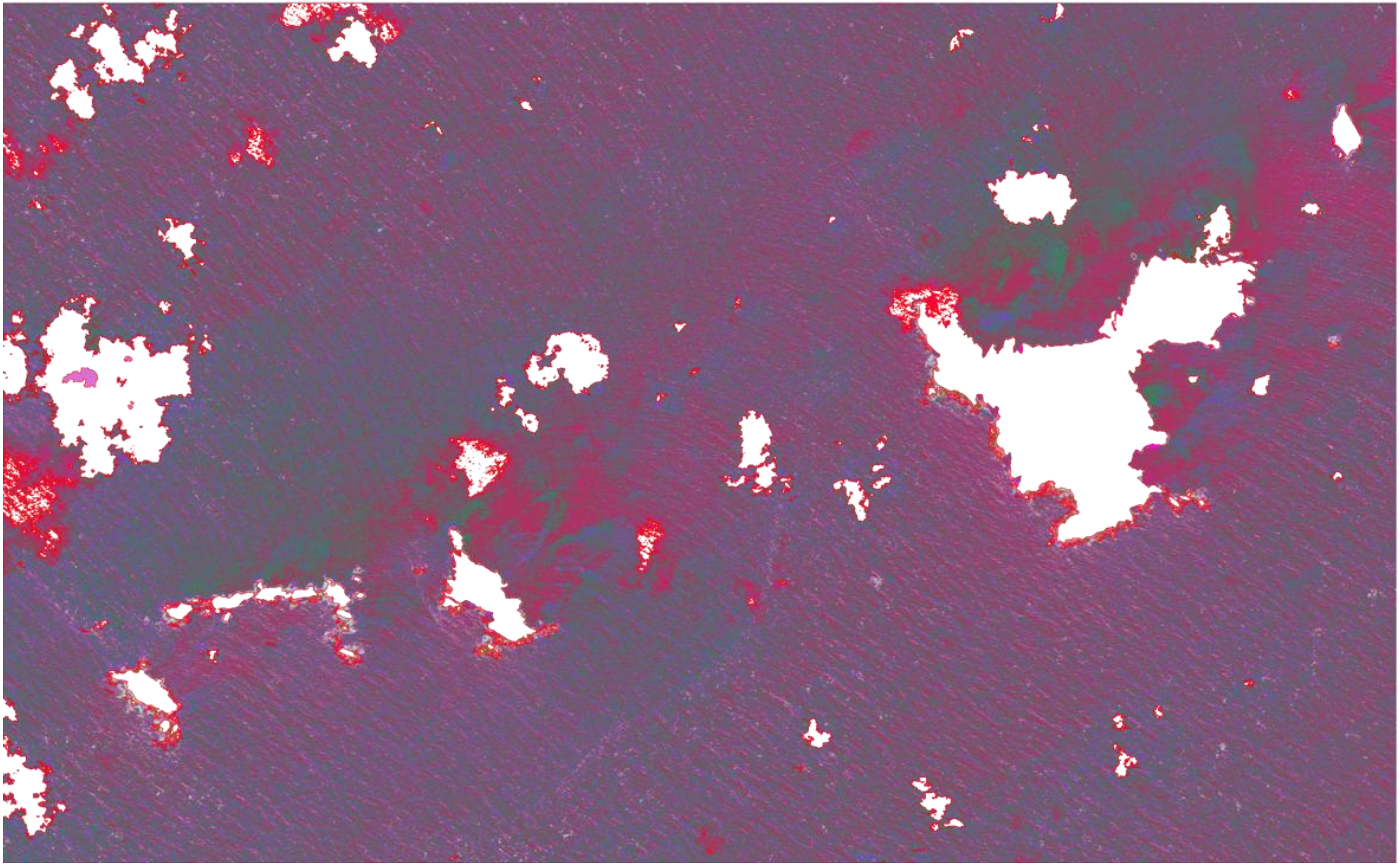
Appendix 2. 22. Majority analysis of maximum likelihood terrestrial classifications (all *WorldView-2* bands)



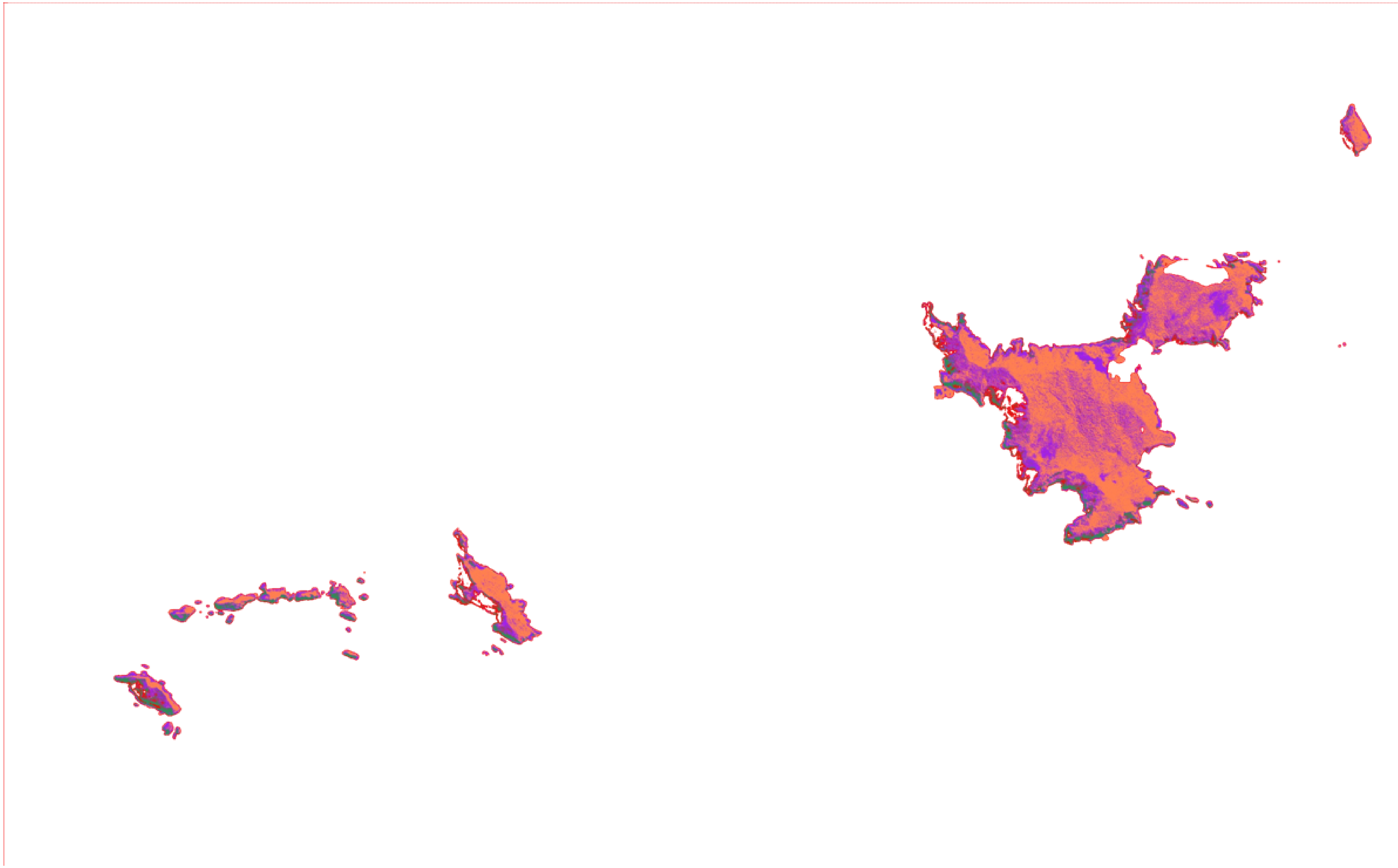
Appendix 2. 23. Unsupervised K-means marine classifications (all *WorldView-2* bands)



Appendix 2. 24. Unsupervised ISODATA marine classifications (all *WorldView-2* bands)



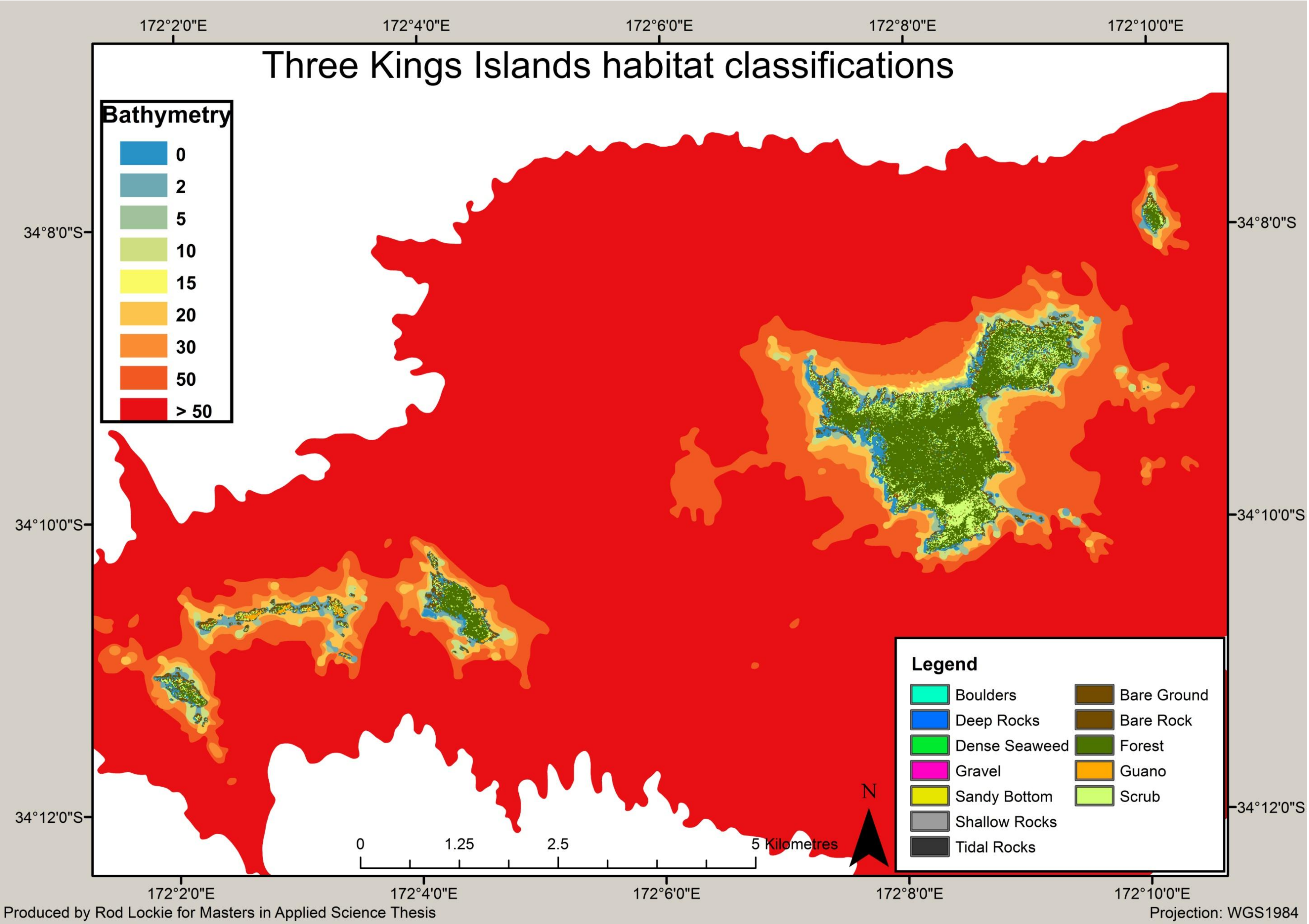
Appendix 2. 25. Unsupervised K-means terrestrial classifications (all *WorldView-2* bands)



Appendix 2. 26. Unsupervised ISODATA terrestrial classifications (all *WorldView-2* bands)

Appendix 3. Habitat map

Appendix 3. 1. Final classification results



Appendix 4. Marxan

Appendix 4. 1. Marxan results 10%, 20% and 30%