Quantifying the Retreating Coastlines of Island Nation Tuvalu from 2014 to 2024 Using Remote Sensing

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INTRODUCTION

Rising sea levels are a consequence of climate change that poses a severe detriment not only to human lives but also to the environment. Glaciers retreating, ice sheets melting, and increasing ocean heat content have caused the global mean sea level (GMSL) to rise by 20 centimeters from 1901 to 2019 with a projected increase of over 2 meters by 2100 (Khojasteh et al., 2023). This alarming increase in GMSL is a threat to Tuvalu's future as an island nation with a maximum elevation of only 4.6 meters (Mugnier, 2019).

As sea levels continue to rise, Tuvalu will continue to bear the harsh effects of rising sea levels. Coastal erosion, residential loss, and tidal flooding are all threats to Tuvalu, an island with a population of 11,310 that consider it their home (Nahib, 2022; Kench aet al., 2018). Failing to realize the severity of the rising sea level will undoubtedly result in the island nation sinking entirely along with cherished homes, agriculture, and culture of Tuvalu's inhabitants.

As such, GIS and remote sensing have been vital for pinpointing which regions in the world are at the highest risk and how it affects the world (Li et al., 2009). However, it can be further used to focus on an area of interest, Vaitupu atoll and Funafuti city of Tuvalu, to provide a detailed analysis of the effects of rising sea levels on that specific area. Due to the much smaller scale, the entire island can undergo analysis which allows for more information to be processed from data sources such as satellite imagery and spectral indices.

This study aims to investigate the rate at which the sea level is rising relative to Tuvalu's coastlines along with the potential long-term effects this phenomenon will have on its inhabitants. Modern satellite imagery and spectral indices will allow the monitoring of Tuvalu's coastlines between 2014 to 2014 and reveal the areas at highest risk of flooding.

METHODOLOGY

This study will focus on Tuvalu, an island nation located in Oceania with longitude of 7.1095° S and latitude of 177.6493° E. Within Tuvalu, this study will further focus on Tuvalu's two main islands: Vaitupu and Funafuti. Vaitupu Island has a longitude of 7.4767° S, and a latitude of 178.6748° E and Funafuti Island has a longitude of 8.5205° S, and a latitude of 179.1980° E. Both islands have bare soil and vegetation as the primary land covers with small residential areas located near the shoreline and inner island. This study will focus on the island's shoreline and the ocean water surrounding it.

The primary data source used for this study is medium spatial resolution satellite imagery from the Landsat-8 satellite manufactured by NASA and acquired from the USGS Earth Explorer website which has already been pre-processed to remove any atmospheric interference. Alongside it, high spatial resolution imagery used in this study were acquired from the Google Maps website with the terrain layer enabled and captured in 2024 by the Airbus satellite and Maxar Technologies. The initial medium spatial resolution satellite imagery used for supervised land classifications consists of ten images for each island with each island captured between the years 2014 to 2024. Each image was captured by the Landsat-8 satellite with a spatial resolution of 30 meters. Due to the limited availability of data from the USGS Earth Explorer website, each image for each year was taken at a different month ranging from January to December with no consistent pattern.

With GIS and remote sensing being the forefront of this study, the software used to conduct it are:

1. ArcGIS Pro - developed by ESRI
2. ERDAS Imagine 2022 - developed by Hexagon Power Portfolio
3. Microsoft Excel 2024 - developed by Microsoft

Supervised Land Classification Methodology

This study performed supervised land classifications to quantify the difference in area (measured in square kilometers) for each land cover (bare soil, vegetation, shoreline, and ocean water) and for each year between 2014 to 2024. For each year and island, composite images were made using the "Composite band" tool in ArcGIS Pro and clipped to a boundary shapefile containing the entire island before any classification was done. ERDAS IMAGINE 2022 was used to perform the supervised land classification for each year using composite images. Signatures of the four land covers were inputted into the "Signature Editor" tool and served as training data for the classification. The signatures were recorded while using Google Maps' high spatial resolution satellite imagery as a reference to ensure each land cover's signature was properly recorded. Accuracy assessments were performed for each year's land classification for both islands with an average overall accuracy of around 89% and an average Kappa statistic of 0.81 (Figure 15, Figure 16).

ArcGIS Pro was used to convert each land cover from the land classification into polygon shapefiles using the "Raster to Polygon" tool. The "Dissolve" tool was used to aggregate similar land covers into one. Each land cover's area was then calculated using the "Calculate Geometry" tool in each land classification's attribute table and recorded in square kilometers. As shown in Figure 3 and 8, the final product was a polygon shapefile for each island between the years of 2014 to 2024 classified with the four land covers: bare soil (dark brown colour), vegetation (dark green colour), shoreline (light blue colour), and ocean water (dark blue colour).

Accuracy assessments were performed on each image by using the "Accuracy Assessment" tool in ERDAS IMAGINE 2022. 75 points were generated with the search count parameter set to 100,000. Stratified Random sampling was chosen to ensure the 50 points were evenly distributed for each land cover. After the points were generated, all the unclassified points were removed to get 50 points in total. To determine the reference land cover type the true color image was used, and for especially difficult sections high-resolution Google Maps imagery was used which was captured in 2024 by the Airbus satellite. The accuracy assessments returned an average overall accuracy of 91% and an average Kappa statistic of 0.8048 for Funafuti Island (Figure 15) and an average overall accuracy of 87% and an average Kappa statistic of .8226 for Vaitupu Island (Figure 16).

NDWI Methodology

NDWI analysis was performed by plotting 50 points on both islands with each point having its coordinates and land cover recorded in a CSV file and transferred into ArcGIS Pro as a points shapefile. Using bands three (green visible light region) and bands five (NIR region) from the Landsat 8 satellite imagery, NDWI values for each island were made using the "Raster Calculator" tool with the formula "*(Float(band3) - Float(band5)) / (Float(band3) + Float(band5))*". In order to record the NDWI values for each of the 50 points, the "Extract Multi Values to Points" tool with the 50 points shapefile as the "input point feature" parameter. This resulted in the 50-points shapefile having its coordinates, land cover, and NDWI value recorded in the attribute table which was then extracted to Microsoft Excel in order to make Figures 13 and 14 for example.

RESULTS

The results of this study present a comprehensive analysis of shoreline changes on the Tuvalu islands of Vaitupu and Funafuti from 2014 to 2024. Using supervised land classifications on medium spatial resolution satellite imagery, each island's four land covers (bare soil, vegetation, shoreline, and ocean water) were quantified for any changes.

Vaitupu Island

For Vaitupu Island, the results are illustrated in Figures 2, 4, 5, 11 and 14. The analysis shows a slight average reduction in the area of shoreline and vegetation classes, with a corresponding increase in bare soil area and little change in ocean water area (Figure 4, 5). Vaitupu experienced a noticeable reduction in vegetation cover, which continued to decline from 2019 to 2024. This trend is further supported by the land cover type change map spanning the entire decade (Figure 2).

The average annual NDWI values for Vaitupu, as shown in Figure 14, indicate a slight overall decreasing trend from 2014 to 2024. This suggests a reduction in surface water presence. Figure 11 further supports this trend, showing a consistent decrease in NDWI values from 2014 to 2024.

The quantified land classification change (Figure 4) reveals that the shoreline has retreated by an average of 0.3 square kilometers per year.

Funafuti Island

The results for Funafuti Island are depicted in Figures 6, 9, 10, 12 and 13. Funafuti showed little average change in vegetation and bare soil areas with an increase in the shoreline area and decrease in ocean water area (Figure 9, 10). The land cover type change from 2014 to 2019 and 2019 to 2024 (Figure 6) highlights substantial losses in vegetation cover near coastal areas. The aggregated land cover class change map (Figure 7) confirms these findings, and the land classification change data (Figure 9) indicates an average shoreline increase of 0.5 square kilometers per year.

NDWI Analysis of Funafuti and Vaitupu Island

The NDWI analysis supports a trend of reduced water levels in areas of Vaitupu, and increased water levels in areas of Funafuti. For Vaitupu, the NDWI maps from 2014 and 2024 (Figure 11) show a decrease in water presence along the coastlines, being instead replaced by areas of bare soil. Funafuti's NDWI comparison between 2014 and 2024 (Figure 12) reveals increased water content in many areas, corroborating the significant changes in land cover observed through satellite imagery. Figure 13 illustrates the changes in NDWI values for Funafuti, showing a clear trend of increasing water presence.

These findings provide a comprehensive view of the temporal and spatial dynamics of shoreline changes in Tuvalu, emphasizing the increasing vulnerability of the islands to rising sea levels and coastal erosion. The data underscores the urgent need for mitigation and adaptation strategies to protect the livelihoods and habitats of Tuvalu's inhabitants.

DISCUSSION

Our investigation aimed to analyze the effects of rising sea levels on the Tuvalu islands of Vaitupu and Funafuti using GIS and remote sensing techniques. The results of this study provide a significant understanding of the spatial and temporal dynamics of shoreline changes and potential flooding risks over the past decade. Our findings indicate a consistent trend of shoreline retreat in Vaitupu and increased inundation risk in Funafuti, particularly in low-lying residential areas and agricultural lands. These outcomes are consistent with global projections of sea-level rise due to climate change, supporting the conclusions drawn by previous studies such as those by Khojasteh et al. (2023) and Mugnier (2019).

Our results corroborate the findings of existing literature that emphasize the vulnerability of low-lying island nations like Tuvalu to rising sea levels. The observed shoreline retreat and increased frequency of tidal flooding align with Kench et al. (2018), who highlighted similar patterns of coastal erosion and habitat loss in Pacific Island nations. However, our study provides more localized insights, focusing specifically on Vaitupu and Funafuti, which allows for a nuanced understanding of the spatial variability in sea-level rise impacts within a single nation.

While our findings generally agree with existing literature, some discrepancies were noted in the rate of shoreline retreat. For instance, Kench et al. (2018) reported a slightly higher average annual rate of shoreline change. These differences could be attributed to variations in data resolution, the time frames considered, and methodological differences in shoreline delineation. Additionally, local factors such as human interventions, coastal engineering projects, and natural variability in sediment transport could also explain these variations.

Several limitations in our study should be acknowledged. Firstly, the reliance on medium spatial resolution satellite imagery (30 meters) from the Landsat-8 satellite may have constrained our ability to detect finer-scale changes in shoreline dynamics. While high-resolution imagery from Google Earth complemented our analysis, the temporal coverage was limited, potentially affecting the continuity and accuracy of our observations. Furthermore, the study's temporal ranges from 2014 to 2024, with annual data points, may not capture short-term episodic events such as storms or seasonal variations that can significantly influence coastal dynamics.

Despite these limitations, our study advances the understanding of sea-level rise impacts on Tuvalu by providing detailed, localized assessments of shoreline changes and flooding risks. The insights gained highlight the urgency for adaptive measures to mitigate the adverse effects of rising sea levels on Tuvalu’s inhabitants. Our findings suggest that immediate actions such as coastal defense structures, habitat restoration, and community relocation plans are essential to safeguard the island nation's future.

While this study and its results focuses on Tuvalu’s two islands, Funafuti and Vaitupu, the techniques and processes used can and should be applied to other island nations experiencing the same detrimental effects of rising sea levels. The Marshall Islands, Micronesia, and the Solomon Islands are just a few small island nations that are facing the same threat of sinking completely under the ocean. Right now, only small island nations are facing the harshest effects, but it is not an exaggeration to say that larger islands and even whole countries will soon face the same threat with the alarming rise of sea level. By bringing awareness, global projects and policies can be implemented to protect these vulnerable islands and ensure the safety of their inhabitants.

Future research should aim to overcome the limitations identified in this study. High-resolution, more frequent satellite imagery, and the integration of in-situ measurements could enhance the accuracy and detail of shoreline monitoring. Additionally, expanding the study to include more islands within Tuvalu and incorporating climate models could provide a comprehensive risk assessment for the entire nation. Long-term monitoring and the application of advanced remote sensing techniques, such as LiDAR and unmanned aerial vehicles (UAVs), could further refine our understanding of the complex interactions between rising sea levels and coastal landscapes.

Overall, our study has demonstrated the critical role of GIS and remote sensing in assessing and monitoring the impacts of climate change on vulnerable island nations. By building on the existing body of knowledge and addressing identified gaps, we can better inform policy and decision-making processes aimed at protecting and preserving the livelihoods and culture of Tuvalu’s inhabitants.

CONCLUSION

In summary, this study has quantitatively demonstrated the significant retreat of coastlines in Tuvalu, specifically on the Vaitupu island, over the past decade due to rising sea levels. Utilizing GIS and remote sensing technologies, we identified consistent patterns of shoreline erosion and increased inundation risks that align with global projections of climate change impacts. These findings not only corroborate existing research but also provide a localized perspective, highlighting the urgent need for adaptive strategies to protect Tuvalu’s vulnerable coastal communities. The insights from this study underscore the importance of implementing immediate mitigation measures such as coastal defense structures and habitat restoration. Furthermore, this research sets the stage for future studies that could employ higher-resolution data and advanced remote sensing techniques to enhance the accuracy and comprehensiveness of coastal monitoring. Ultimately, our work contributes to the broader understanding of climate change impacts on small island nations and supports the development of informed policies aimed at safeguarding their future.

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APPENDICES

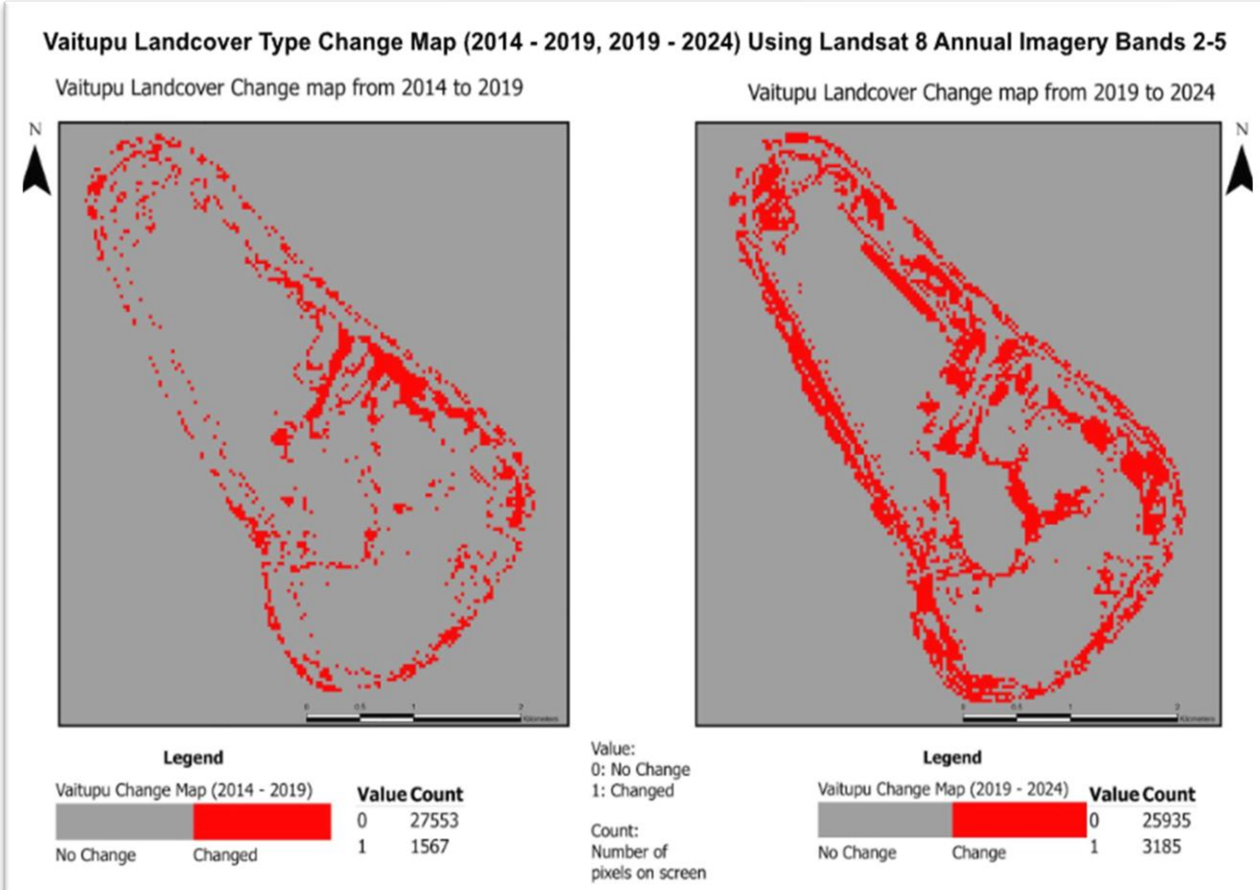

Figure 1: Vaitupu Land Cover Type Change Map (2014 - 2019 and 2019 - 2024)

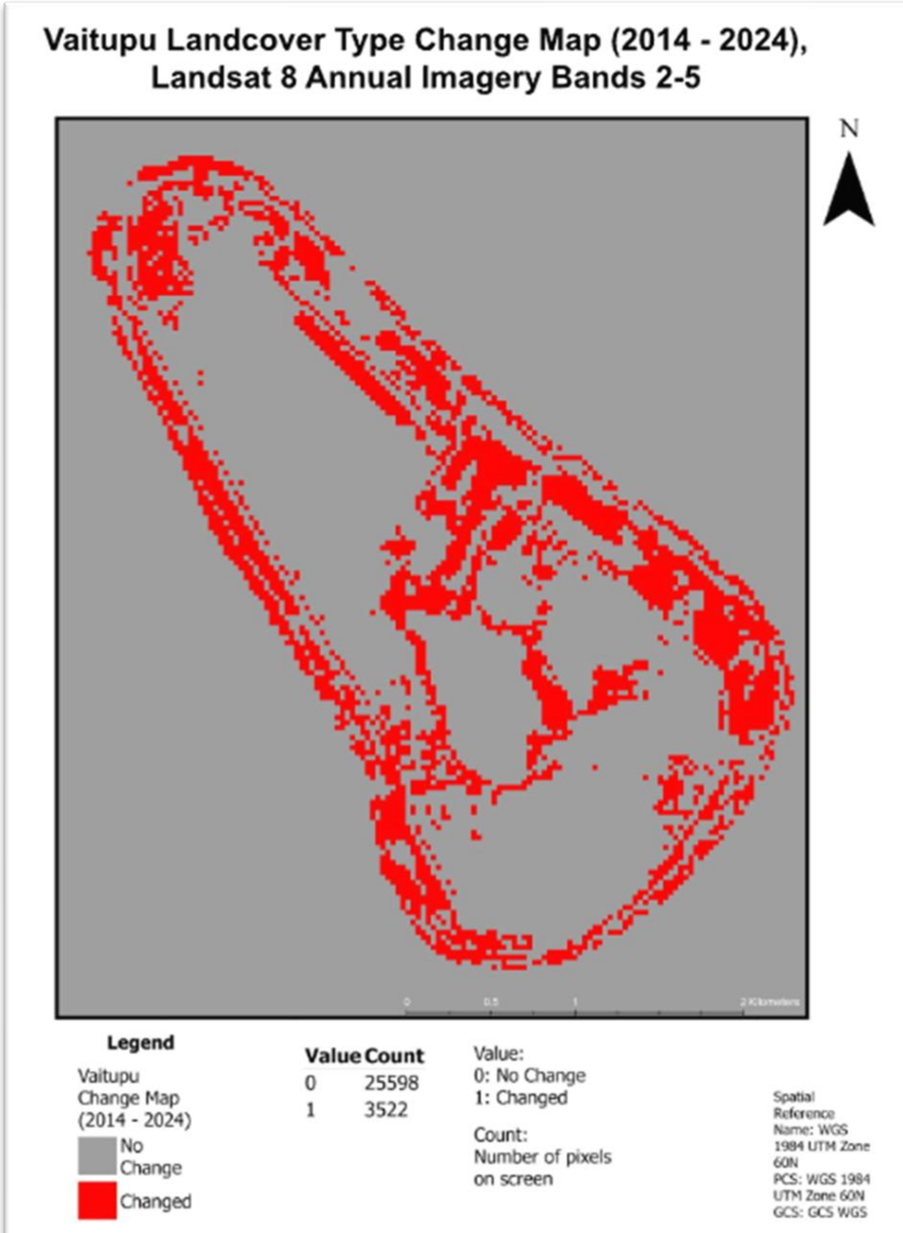

Figure 2: Vaitupu Land Cover Type Change Map (2014 to 2024)

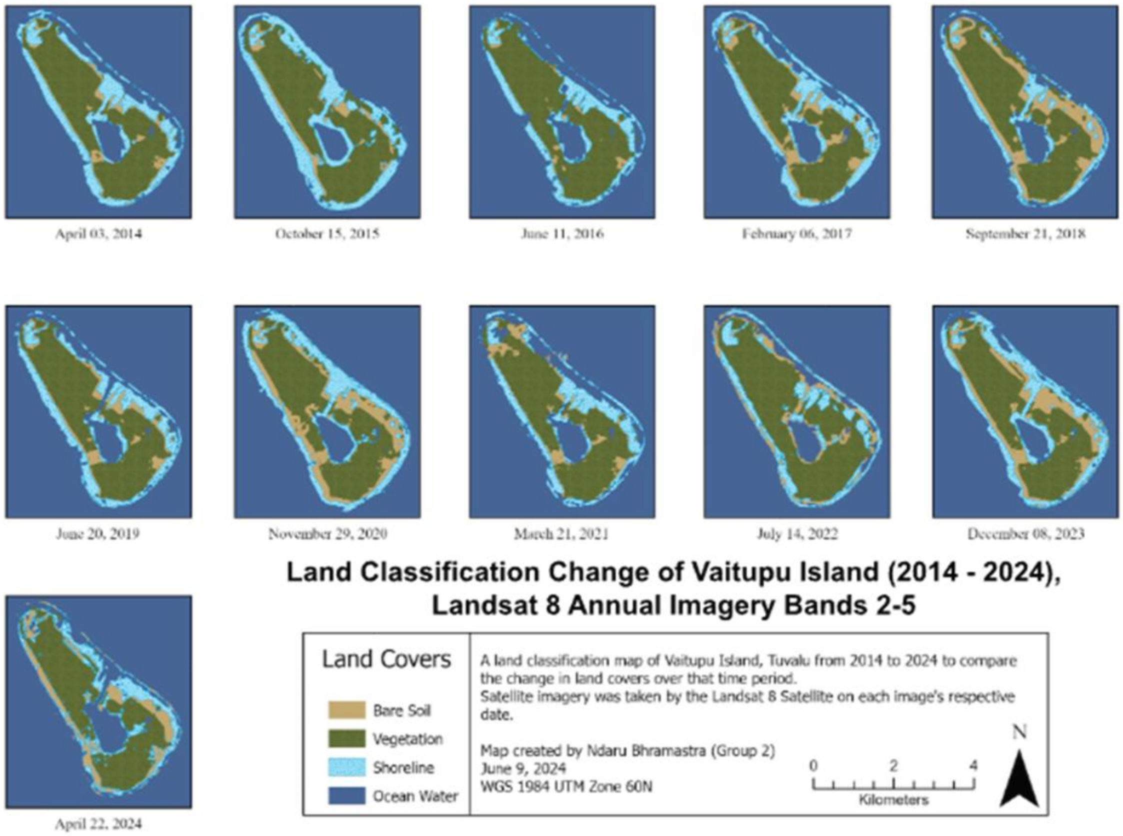

Figure 3: Land Classification Change of Vaitupu Island (2014 - 2024)

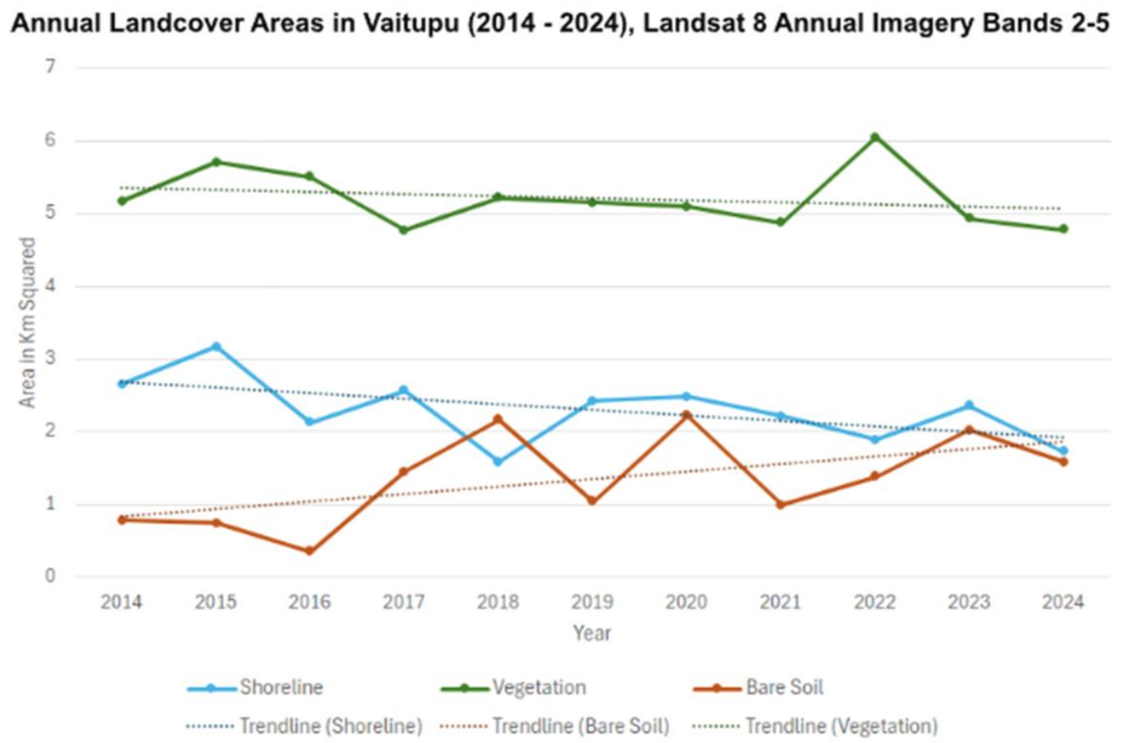

Figure 4: Land cover area change of Vaitupu without water land cover (2014 - 2024)

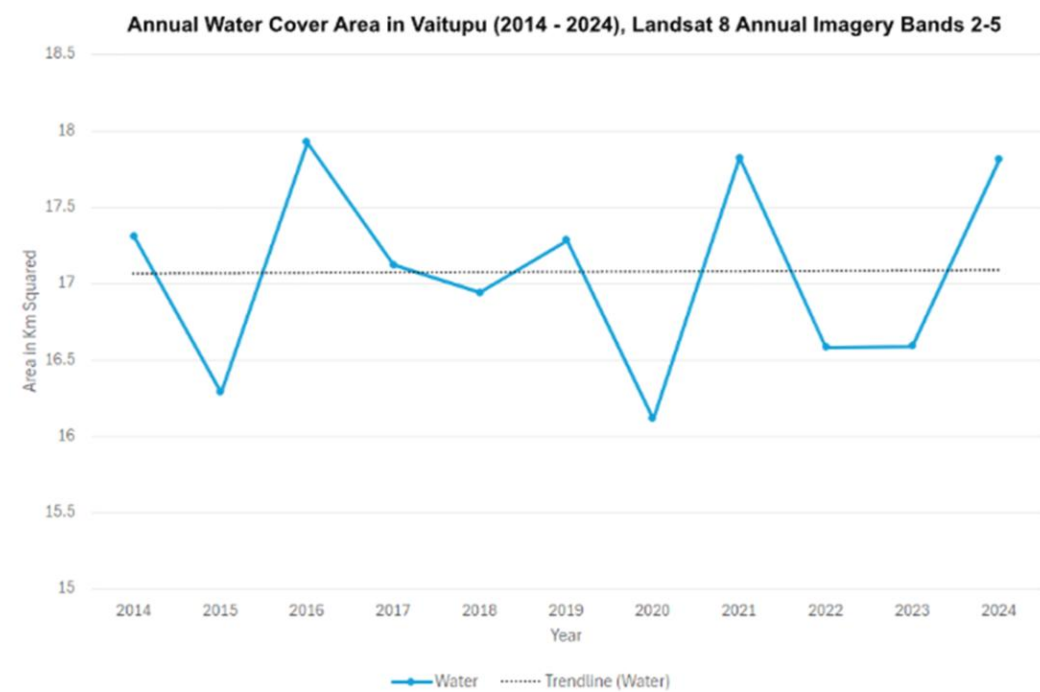

Figure 5: Water land cover area change of Vaitupu (2014 - 2024)

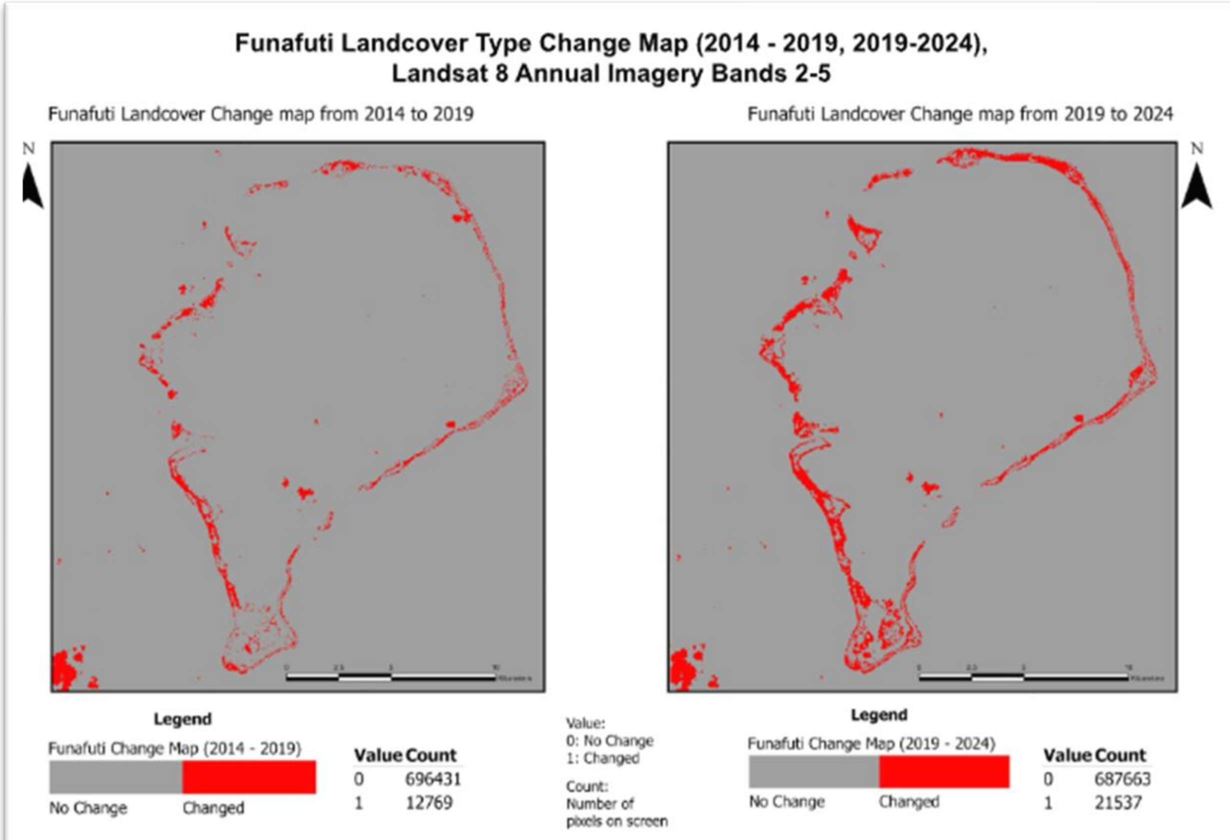

Figure 6: Funafuti Land Cover Type Change Map (2014 - 2019 and 2019 - 2024)

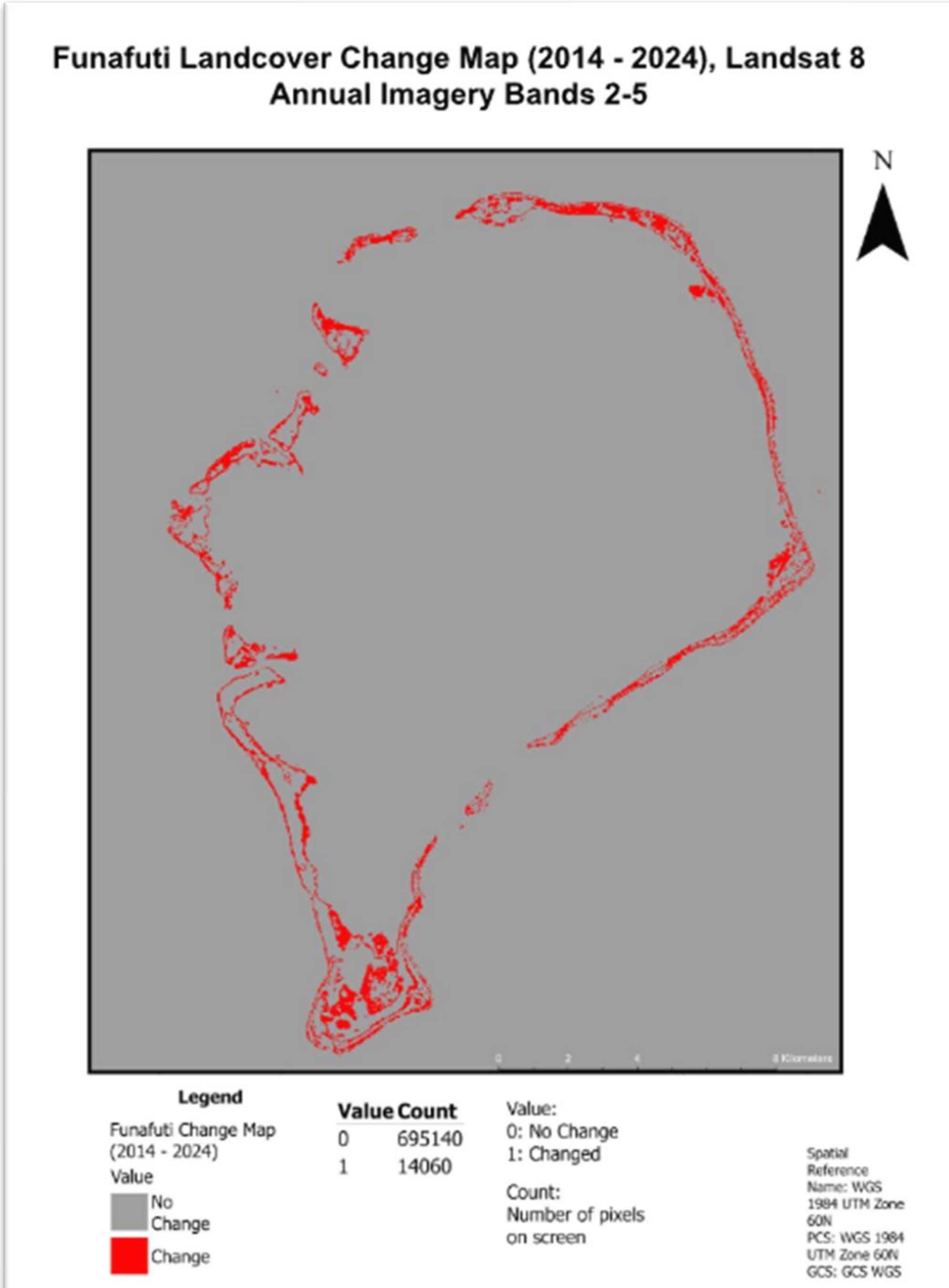

Figure 7: Funafuti Land Cover Class Change Map (2014 to 2024)

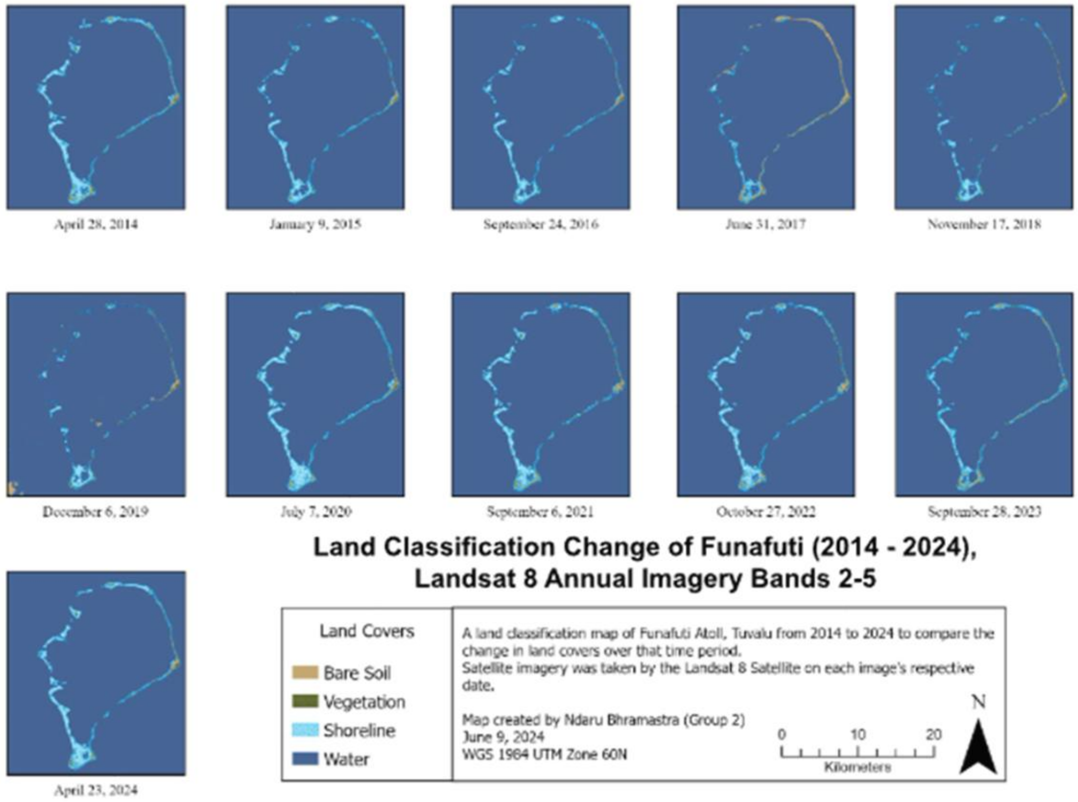

Figure 8: Land Classification Change of Funafuti (2014-2024)

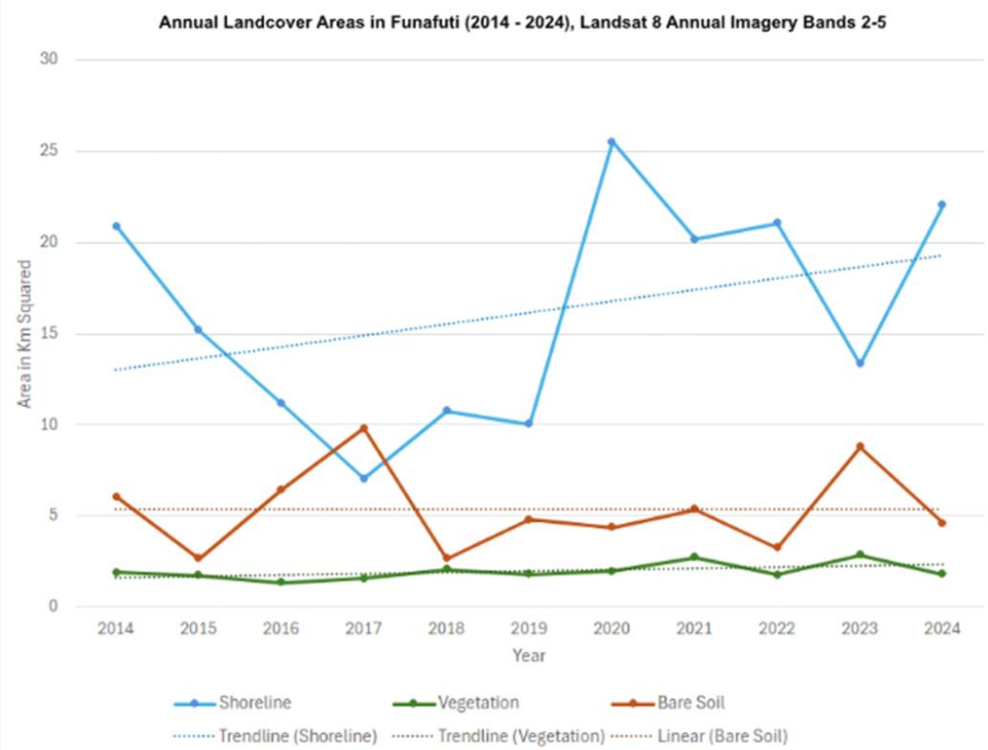

Figure 9: Land cover area change of Funafuti without water land cover (2014 - 2024)

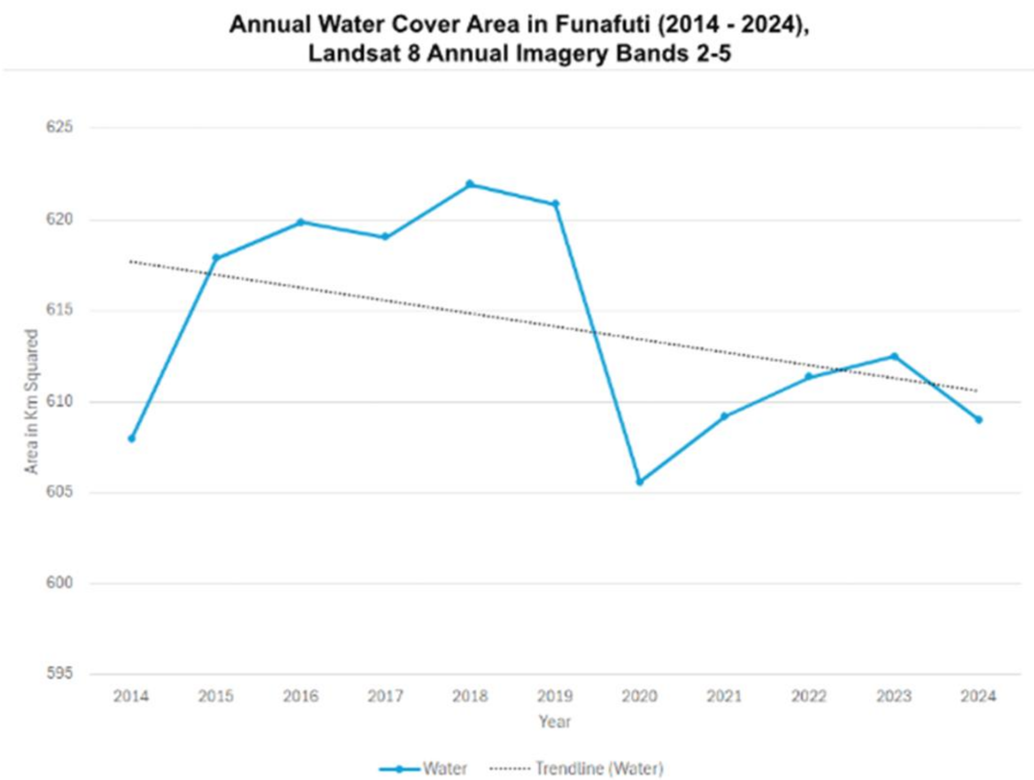

Figure 10: water land cover area change of Funafuti (2014-2024)

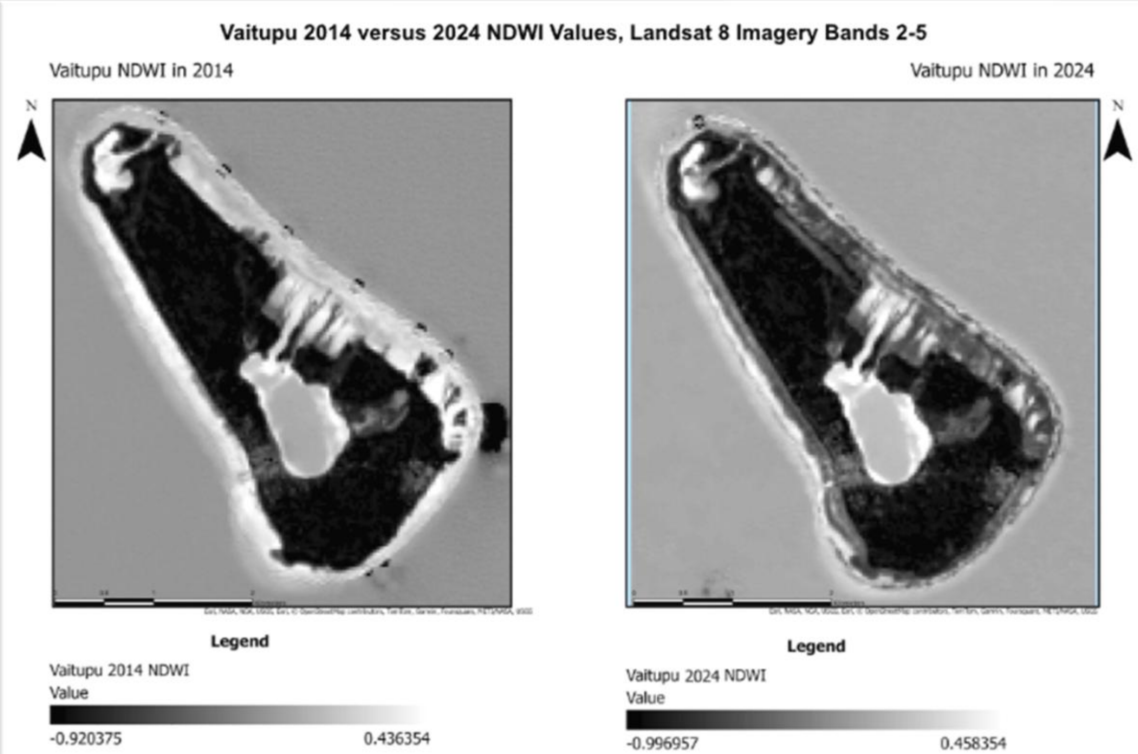

Figure 11: Vaitupu NDWI in 2014 versus Vaitupu NDWI in 2024

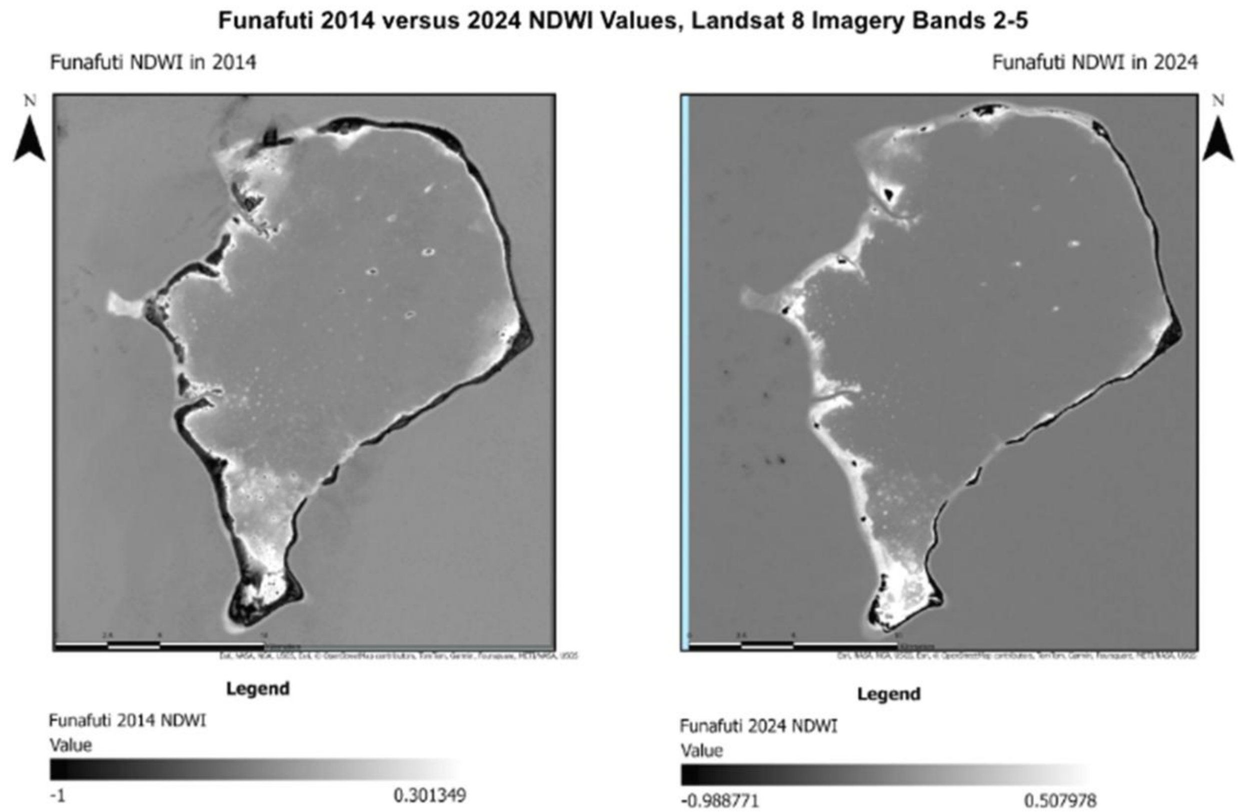

Figure 12: Funafuti NDWI in 2014 versus Funafuti NDWI in 2024

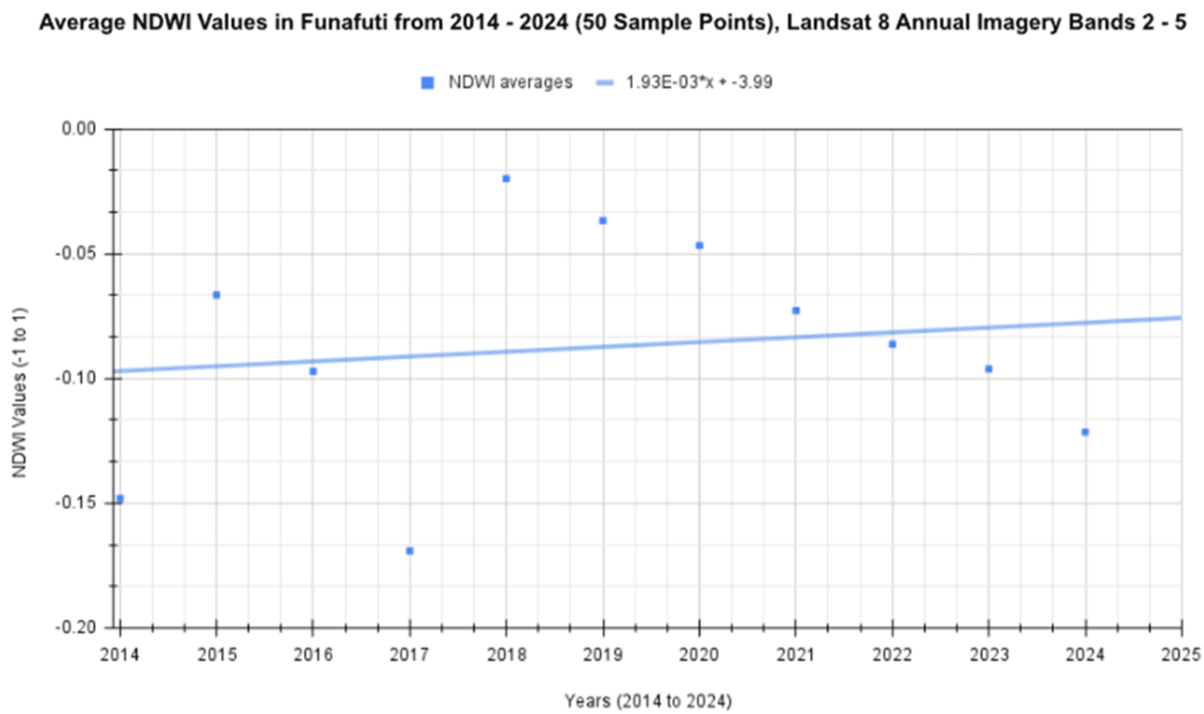

Figure 13: Funafuti NDWI Changes

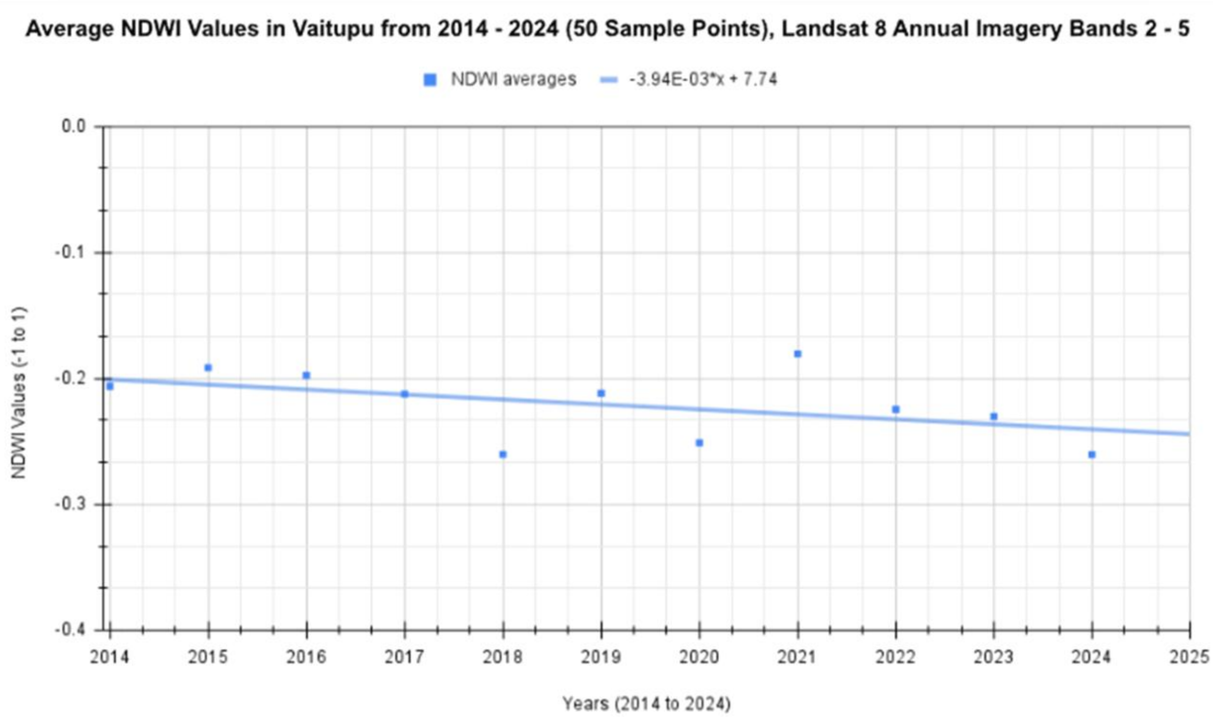

Figure 14: Vaitupu NDWI Changes

Supervised Classification Image Accuracy Assessment Results of Funafuti, Tuvalu Using Unclassified, Bare Soil, Vegetation, Shoreline and Water Classes with Landsat 8 Annual 2014 - 2024 Satellite Imagery, Bands 2 - 5		
Year	**Overall Classification Accuracy (%)**	**Overall Kappa Statistics**
2014	94	0.6462
2015	88	0.8362
2016	86	0.8112
2017	90	0.8712
2018	96	0.8175
2019	96	0.7854
2020	94	0.6774
2021	96	0.8501
2022	90	0.8625
2023	88	0.8343
2024	90	0.8603

Figure 15: Funafuti Image Accuracy Assessment Results

Supervised Classification Image Accuracy Assessment Results of Vaitupu, Tuvalu Using Unclassified, Bare Soil, Vegetation, Shoreline and Water Classes with Landsat 8 Annual 2014 - 2024 Satellite Imagery, Bands 2 - 5		
Year	**Overall Classification Accuracy (%)**	**Overall Kappa Statistics**
2014	80	0.7269
2015	83	0.7778
2016	80	0.7268
2017	78	0.7004
2018	96	0.9548
2019	94	0.8747
2020	94	0.9200
2021	90	0.8644
2022	88	0.8370
2023	82	0.7667
2024	92	0.9000

Figure 16: Vaitupu Image Accuracy Assessment Results