Information Visualisation Project COMP3045 UNMC SPM1 23-24

Empowering Coral Reef Conservation Through Data Visualization

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This study provides an extensive dataset of Exclusive Economic Zones (EEZs) for 108 coral reef nations and territories, categorized by reef reliance, adaptive capacity, and societal vulnerability. The Reef Dependence Index considers factors like reef-associated population, fisheries employment, exports, nutritional dependence on fish, tourism, and coastline conservation. The Social Vulnerability Index combines data on reef threats, adaptive capacity, and reef dependency. It aids coral reef conservation efforts by offering a comparative analysis to identify vulnerable locations and guide conservation strategies.

CCS CONCEPTS • Human-centred computing → Visualization → Information visualization • Information systems → Data management systems → Geographic information systems • Applied computing → Earth and atmospheric sciences → Oceanography • Applied computing → Environmental sciences

Additional Keywords and Phrases: Coral reefs, Reef dependence, Adaptive capacity, Social vulnerability, Reef-associated livelihoods, Coastal communities, Conservation and management, Geospatial analysis, Decision-making support

1 INTRODUCTION

When we think of corals, we often imagine vibrant tropical waters teeming with life, particularly the stony corals that form reefs. However, corals come in various forms, including soft and deep-water species found in colder, darker environments. Majority of corals are colonial organisms made up of numerous individual animals called polyps. Each polyp has a single opening, the mouth, surrounded by tentacles used for various purposes like defence, feeding, and cleaning. Food is ingested through the mouth, and waste is expelled through the same opening. Corals typically feed during the night, employing stinging cells called nematocysts located in their tentacles and outer tissues to capture prey. These cells, similar to those found in jellyfish, deliver potent toxins to immobilize prey, which can range from tiny zooplankton to small fish. Additionally, corals may also gather organic particles using mucous films and strands, drawing them into their mouths for consumption [1].

Coral reefs stand out as incredibly diverse and invaluable ecosystems, hosting a wealth of species unmatched by any other marine environment. With around 4,000 fish species, 800 hard coral species, and countless others yet to be discovered, coral reefs are considered hotspots of biodiversity, holding potential for ground-breaking medical discoveries. These ecosystems are vital for supporting both commercial and subsistence fisheries, as well as generating income through tourism and recreational activities. The economic significance of coral reefs is substantial, with an estimated commercial value exceeding $100 million in the United States alone. Local economies benefit significantly from activities like diving tours, recreational fishing, and hospitality services near reef areas. Moreover, coral reef structures play a crucial role in protecting coastlines, absorbing a staggering 97 percent of wave energy, and shielding communities from the impacts of storms and floods. However, despite their ecological and economic importance, coral reefs face severe threats from pollution, disease, and habitat destruction. Damage to these reefs not only diminishes their ability to sustain diverse marine life but also undermines their value as tourist destinations, impacting both local communities and economies [2].

1.1 Goal

The major purpose of this study is to undertake a comprehensive comparative examination of nations and territories that host coral reef systems, with an emphasis on determining their reliance on reefs, ability to resist reef loss, and socioeconomic vulnerabilities associated with reef degradation. My goal in conducting this research is to increase awareness about the issues that coral reef ecosystems face, as well as to identify danger areas. Through the sharing of our findings, I hope to mobilise focused conservation and management efforts to protect these precious marine habitats. The goal of visualisations and analysis is to acquire insights into the current state of coral reef habitats, identify regions of high sensitivity to coral bleaching, and give useful information for conservation and management initiatives.

1.2 Problem Statement

Human activities, including pollution, overfishing, destructive fishing methods, coral collection for the aquarium trade, and climate change, pose significant threats to coral reefs worldwide. Pollution from land-based sources introduces sediments, nutrients, chemicals, and debris into reef waters, fuelling algae growth that can smother corals. Activities like blast fishing and cyanide fishing indiscriminately kill marine life and severely damage coral reefs. Climate change exacerbates reef degradation by causing ocean warming, altered storm patterns, and rising sea levels, increasing the frequency of coral bleaching events and intensifying storm damage [3]. Through this initiative, I hope to contribute valuable insights that will aid in steering targeted conservation measures, thereby ensuring the resilience and continuity of coral reef ecosystems and the human communities they support.

2 REALATED WORK

The "Reefs at Risk Revisited" technical notes from the World Resources Institute, authored by Lauretta Burke and Katie Reytar in 2011, detail an extensive analysis aimed at assessing global coral reef threats. It incorporates a diverse array of data sources to model human activity impacts, climate change, and ocean acidification on coral reefs. The report stratifies threats into local and global categories and employs a geographic information system (GIS) for comprehensive mapping and trend projection. This work is significant for highlighting at-risk regions and serves as an essential resource for researchers, conservationists, and policymakers in coral reef management and conservation efforts [4].

Since its establishment in 2000, CRW has offered users the SST Anomaly product, designed to monitor the variance between the present Sea Surface Temperature (SST) and the long-term average SST derived from the MM climatology. While this doesn't specifically track extreme heat stress linked to coral bleaching, it enables users to monitor shifts in local conditions, providing a broader perspective on SST anomalies. This broader perspective can help contextualize events of heat stress at levels relevant to coral bleaching, along with other deviations from the typical climatic conditions. It's important to note that the SST Anomaly product registers positive values when the current SST exceeds the climatological average and negative values when the current SST falls below this average [6].

The Coral Bleaching HotSpot product utilizes the MMM climatology to generate a daily anomaly metric aimed at depicting the heat stress encountered by corals. It serves as a measure to gauge the extent of heat stress experienced on a daily basis. Heat stress levels considered harmful are identified when the HotSpot value equals or exceeds 1 degree Celsius [6,7]. Due to its spatial resolution of 0.05 degrees, which translates to roughly 5 × 5 km, and its derivation from SST adjusted to a depth of 20 cm, the HotSpot (HS) metric should be viewed as a general measure of daily heat stress across reefs. This is particularly relevant considering the diverse thermal thresholds observed among different coral species [8].

3 METHODS AND DESIGN

3.1 Data Preparation

Loading a shape data frame using the'st_read' function, which allows for direct reading of PostGIS tables via the DBI and RPostgreSQL interfaces and transforming Well-Known Binary geometries into spatial feature objects (sfc) [9]. The `st_read` function is part of the `sf` package in R. This package is used for working with spatial data, particularly for handling vector data in the Simple Features (sf) format. The `st_read` function is used to read spatial data from various formats, such as shapefiles, GeoJSON, and databases, into R as spatial objects. Using read_csv() to read the CSV dataset file. The `read_csv` function is available in the `readr` package in R, which is part of the tidyverse. This function is specifically designed for reading comma-separated values (CSV) files into R data frames.

`dplyr` represents the evolution of plyr, with a focus on enhancing tools for managing data frames, hence the inclusion of the "d" in its name. Its primary objectives are to streamline the essential data manipulation tasks required for data analysis within R, to deliver exceptionally fast performance for data stored in memory using C++, and to offer a consistent interface for working with data regardless of its storage location, whether in a data frame, a data table, or a database [10].

`tidyr` is a recent addition to R's collection of packages designed to simplify the organization of your data into a "tidy" format. Tidy data is structured in a way that facilitates various tasks such as data manipulation using `dplyr`, visualization using `ggplot2` or `ggvis`, and modelling using R's extensive range of modelling packages. By adhering to tidy data principles and utilizing tidy tools, users can streamline their workflow, spending less time grappling with data formatting issues and more time gaining insights from their analyses [11].

3.2 Geographic Coordinate System Transformation

To handle the antimeridian problem in the dataset, two methods were employed. In the first method, the `st_transform()` function from the `sf` package in R was utilized to convert the MULTIPOLYGON geometry data to the WGS 84 geographic coordinate system, thereby addressing issues related to coordinate reference systems [12]. Subsequently, the `st_wrap_dateline()` function, also from the `sf` package, was applied to manage geometries crossing the antimeridian (180° longitude).

The second method addressed both antimeridian problems in latitude and longitude. Initially, non-numeric characters were removed from these columns, and the values were converted back to numeric format. Rows with missing longitude or latitude values were then eliminated. For longitudes less than -180, the `mutate()` function from the `dplyr` package was used to adjust them by adding 360, ensuring they fell within the valid range of -180 to 180. Similarly, latitude values greater than 90 or less than -90 were replaced with NA to address invalid latitude values.

3.3 Visualization

3.3.1 Interactive Bubble Chart

An interactive bubble map in Plotly in R allows for dynamic exploration and visualisation of geographical data by utilising bubbles of varied sizes to represent data points. The goal is to increase interactivity within the chart by allowing users to zoom in on specific regions of interest, acquire additional information about individual circles by hovering, and export the chart to PNG format [14]. Users can, for example, interactively increase or decrease the category of the bubble, hover over bubbles to display deeper information, export the map to various file formats, and optionally include extra interactive elements such as slider controls for time series data or dropdown menus for categorical variables. These interactive capabilities are enabled by using the 'ggplotly()' function from the 'plotly' package, which converts any ggplot2 chart object into an interactive visualisation. Additionally, customising tooltip material enhances the interaction experience [13]. The integration of Plotly and R simplifies the production of these interactive visualisations, allowing users to obtain deeper insights from their geographical datasets.

3.3.2 Choropleth Map

A choropleth map is a type of thematic map designed to visualize statistical data through colour shading or pattern techniques. It depicts geographical areas divided into units, each representing specific data values. By colouring, shading, or patterning these units based on the associated data variable, choropleth maps effectively illustrate variations or patterns across the depicted geographic area [14].

3.3.3 Pie Chart

A pie chart visually represents data values as segments of a circle, each segment distinguished by a different colour. These segments are labelled, and the numerical values corresponding to each segment are typically displayed within the chart [15].

3.3.4 Histogram

A histogram is a visual tool frequently employed to illustrate the distribution of numerical data. It partitions the values of a numerical variable into intervals called "bins" and tallies the number of observations falling within each bin. This columnar representation of binned counts provides a clear and intuitive depiction of the distribution of values within the variable [16].

3.3.5 Heatmap

A heatmap is a two-dimensional visual representation of data using colours, with each colour representing a distinct value. A heatmap is a two-dimensional graphical representation of data that uses colour to indicate several elements. Heatmaps are a useful visual tool for viewers, allowing for the rapid conveyance of statistical or data-driven information [17].

3.4 Interaction with Shiny App

Shiny, an R package, facilitates the creation of interactive web applications capable of executing R code on the backend. With Shiny, users can develop standalone applications for web hosting, integrate interactive charts into R Markdown documents, or construct dashboards. Shiny empowers users to build robust interactive web applications entirely within R. By crafting a user interface and server in R, Shiny generates the necessary HTML, CSS, and JavaScript to showcase the application online. Since the application executes R code on the backend, it can perform any R computation feasible on a desktop [18].

4 IMPLEMENTATION

4.1.1 Data Loading and Preprocessing

Loads the spatial data from a shapefile (`st_read()` from the `sf` package) as `shape_data` and the NOAA coral reef data from a CSV file (`read.csv()`) as `coral_data`. For description of `shape_data` please refer to Table *1*: Data structure of the spatial data `shape_data`, and for description of `coral_data` please refer to Table *2*: Data structure of CSV file NOAA coral reef data `coral_data`.

Data preprocessing steps are performed, including removing non-numeric characters from longitude and latitude columns, handling missing values, adjusting longitude and latitude values to valid ranges, and converting data types as necessary.

4.1.2Static Visualizations

Packages `ggplot2` is used to create various visualizations. The `viridis` colour palette is widely used for colour mapping in various visualizations.

1. Heatmaps are created using `geom_tile()` to visualize spatial distributions of variables like Coral Bleaching Alert Areas and Hotspot Areas. The map uses a colour scale ranging from purple to yellow, where purple indicates areas with the highest alert levels for coral bleaching, and yellow represents areas with lower alert levels.
2. Pie charts (`coord_polar()`, `geom_bar()`) are used to show the distribution of the Bleaching Alert Area 7-day Maximum Composite. The chart is generated from data where the variable CRW_BAA_7D_MAX_mask, presumably related to coral bleaching heat stress levels, is counted, and expressed as a percentage of the total non-missing data points. The pie chart is color-coded to represent different categories or levels of bleaching heat stress, with the percentages displayed within each pie segment.
3. Histograms (`geom_histogram()`) are used to visualize the distributions of CRW_SST and CRW_SSTANOMALY, leveraging the `tidyr` package for data reshaping with `pivot_longer()`. The histograms represent the distribution of

sea surface temperature (CRW_SST) and sea surface temperature anomaly (CRW_SSTANOMALY) from the coral_data dataset. The temperatures are on the x-axis, and the y-axis represents the percentage of the dataset that falls into each temperature bin, where each bin has a width of 0.5°C.

4.1.3 Interactive Bubble Chart

Implement an interactive bubble chart using the `plotly` library to visualize the relationship between reef dependence, adaptive capacity, and social vulnerability indices. The `plot_ly()` function is used to create the base plot, and `add_markers()` is employed to add the bubble markers. The x-axis represents the Reef Dependence Index, the y-axis represents the Adaptive Capacity Index, and the size and colour of the bubbles correspond to the Social Vulnerability Index and Vulnerability Category, respectively. The size of each bubble corresponds to the Social Vulnerability Index (Vuln_Indx), which is a measure of the susceptibility of a region or country to the potential adverse effects of coral reef degradation or loss. The larger the bubble, the higher the social vulnerability. The colour of each bubble represents the Vulnerability Category, which is a classification based on the Social Vulnerability Index. The categories range from "Very High" (red) to "High" (orange), "Medium" (light green), and "Low" (dark green) vulnerability. Tooltips are added to display additional information about each data point using the `text` argument.

4.1.4 Interactive Shiny Application

The `shiny` package to build an interactive web application for exploring the coral reef data.

The user interface (`ui`) is defined using Shiny's reactive components, such as `fluidPage()`, `selectInput()`, `leafletOutput()`, `plotlyOutput()`, and `conditionalPanel()`. The server logic (`server`) is implemented to handle user inputs, filter data, and render appropriate outputs (choropleth maps, interactive maps, and the bubble chart). The `leaflet` package is utilized to create interactive maps, allowing users to visualize data points on a geographic map and filter based on the Social Vulnerability Index range. The `leaflet.extras` package provides additional functionality, such as marker clustering (`markerClusterOptions()`). A colour palette for the vulnerability categories using `colorFactor()` from the `RColorBrewer` package.

The `createVulnerabilityMap()` function is defined to create a Leaflet map with circle markers representing the data points. The markers are colored based on the vulnerability category, and popups display additional information about each data point.

The Shiny user interface (`ui`) is defined using `fluidPage()` and various layout functions. It provides three main views: "Choropleth Maps", "Interactive Map" and "Bubble Chart of Reef Dependence and Adaptive Capacity".

a. For the "Choropleth Maps" view, a dropdown menu allows the user to select the map category (reef dependence, adaptive capacity, or social vulnerability), and another dropdown menu allows the user to select the specific category within the chosen map category.
b. For the "Interactive Map" view, the user interface includes a slider that allows the selection of a specific range of Social Vulnerability Index values. The map then highlights only the regions or countries that fall within the selected range, making it easier to identify areas with similar levels of social vulnerability related to coral reefs.
c. For "Bubble Chart of Reef Dependence and Adaptive Capacity" view, refer to 4.1.3.

The Shiny server logic (`server`) is defined to handle user inputs and render the appropriate outputs.

d. For the "Choropleth Maps" view, it filters the data based on the selected map category and category, transforms the data to the WGS 84 coordinate system, and renders a Leaflet map with polygons coloured based on the selected category.

e. For the "Interactive Map" view, it filters the data based on the selected social vulnerability index range and renders a Leaflet map with circle markers coloured based on the vulnerability category. The `createVulnerabilityMap()` function is used to create the interactive map.
f. For "Bubble Chart of Reef Dependence and Adaptive Capacity" view, please refer to 4.1.3.

4.1.5 Spatial Data Handling

The `sf` package is extensively used for handling spatial data, including coordinate reference system transformations (`st_transform()`), handling invalid geometries (`st_is_valid()`, `st_make_valid()`), and calculating centroids (`st_centroid()`). The `rgeos` package is also imported for spatial data operations.

The process involves several steps to handle geographic data effectively. Initially, the `st_transform` function from the `sf` package is utilized to reproject the geographic data loaded into the `shape_data` spatial object. By specifying `crs = 4326`, which corresponds to the WGS 84 coordinate reference system, the data is transformed to a widely recognized standard used in mapping and navigation systems like GPS. Subsequently, the `st_wrap_dateline` function, also from the `sf` package, is employed to address spatial objects crossing the antimeridian, ensuring accurate representation and processing. This function wraps features crossing the dateline and sets the dateline offset appropriately. Additionally, the `gsub` function is applied to the `coral_data` dataframe to remove non-numeric characters from the longitude and latitude columns, ensuring data consistency. The longitude and latitude columns are then converted back to numeric data types using the `as.numeric` function. Rows with missing longitude or latitude values are removed from the data frame using the `is.na` function. Furthermore, adjustments are made to longitude values less than -180 by adding 360, and latitude values greater than 90 or less than -90 are set to NA. These steps collectively ensure the integrity and usability of the geographic data for further analysis.

4.1.6 Color Mapping and Legends

1. The `RColorBrewer` package is employed to define colour palettes for mapping vulnerability categories (`colorFactor()`).
2. Legends are added to the interactive maps using `addLegend()` from the `leaflet` package.

5 RESULTS

5.1 Shiny App with Interactive Bubble Plot

The chart visualizes the relationship between reef dependence on the x-axis and adaptive capacity on the y-axis for different regions or communities. The size of the bubbles represents the social vulnerability category, with larger bubbles indicating higher vulnerability.

In the upper-right quadrant, there is one small green bubble representing a region with low social vulnerability, low reef dependence, and high adaptive capacity. In the upper-middle area, there are several medium-sized yellow and blue bubbles indicating regions with medium and high social vulnerability respectively, moderate to moderate reef dependence, and moderate adaptive capacity. Towards the lower-right, there are a few large red bubbles showing regions with high social vulnerability, high reef dependence, but relatively lower adaptive capacity.

The regions or countries with larger bubbles (higher Social Vulnerability Index) tend to have higher Reef Dependence and lower Adaptive Capacity, indicating a positive correlation between social vulnerability and reef dependence, but a negative correlation with adaptive capacity. Conversely, the regions or countries with smaller bubbles (lower Social Vulnerability Index) generally have lower Reef Dependence and higher Adaptive Capacity.

In summary, areas with high reef reliance coupled with low capacity to adapt tend to exhibit higher overall social vulnerability. In contrast, areas with lower reef dependence and greater adaptive abilities display lower social vulnerability levels based on this visualization.

Figure 1: Bubble Chart of Reef Dependence and Adaptive Capacity

5.2 Shiny App with Choropleth Map

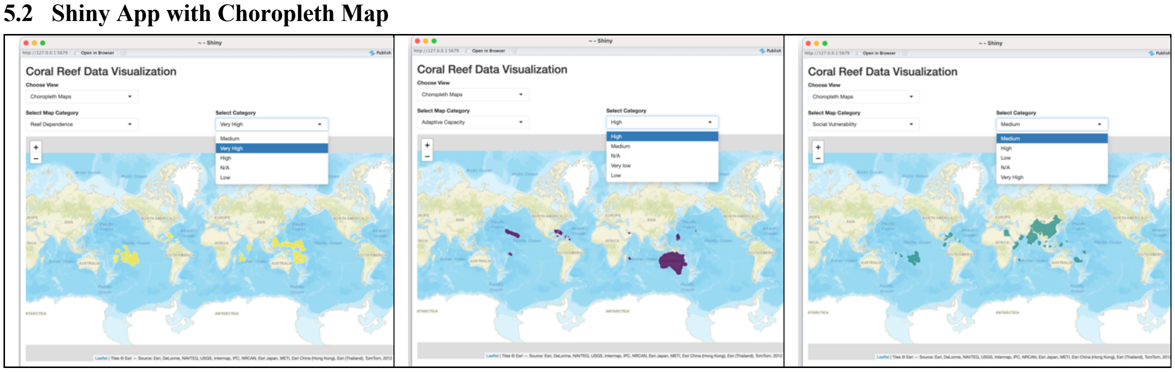

Figure 2 Shiny App with Choropleth Maps

5.2.1 Reef Dependent:

To illustrate the "Reef Dependence" category, representing varying levels of reliance on coral reefs across global regions, a map is employed. The map utilizes a diverging colour scheme, where different shades indicate distinct levels of dependence. The map is coloured using a diverging colour scale ranging from green (low dependence) to dark blue (medium dependence).

Visualizing the "Reef Dependence" category through a map provides a comprehensive depiction of the extent to which different regions rely on coral reefs for various socio-economic activities. By categorizing countries into quartiles based on their level of dependence, the visualization enables policymakers and stakeholders to identify areas with high reliance on coral reefs for livelihoods, food security, tourism, and cultural heritage. Understanding the distribution of reef dependence is crucial for informing conservation and management strategies, as it highlights areas where the sustainable use and preservation of coral reef ecosystems are paramount. Additionally, by employing a diverging colour scheme to represent different levels of dependence, the visualization facilitates easy interpretation, allowing viewers to discern regions with varying degrees of reliance on coral reefs at a glance.

5.2.2 Adaptive Capacity

To show the "Adaptive Capacity" category, which represents the ability of regions to adapt to potential changes or threats to coral reefs. The map uses a sequential colour scale from light purple (very low adaptive capacity) to dark purple (high adaptive capacity).

Visualizing the "Adaptive Capacity" index provides insights into a country's ability to respond and adapt to changes or threats affecting coral reefs. This index is derived from various socio-economic factors such as economic resources and governance structures. By categorizing countries into quartiles ranging from very low to high adaptive capacity, the visualization highlights the relative readiness of each country to cope with challenges posed by coral reef degradation. Countries with higher scores in the Adaptive Capacity index are better equipped to implement strategies and policies aimed at mitigating the impacts of coral reef changes, potentially leading to more effective conservation and management efforts.

5.2.3Social Vulnerability

To visualize the "Social Vulnerability" category, which represents the vulnerability of communities or regions to potential threats or impacts related to coral reefs. The map uses a diverging colour scale ranging from light green (low vulnerability) to dark green (high vulnerability), with medium vulnerability shown in blue.

Mapping the "Social Vulnerability" category offers valuable insights into communities' susceptibility to coral reef-related threats. By categorizing countries into quartiles based on vulnerability, the visualization provides a nuanced understanding of socio-economic dynamics and resilience. Utilizing a diverging colour scale allows for quick identification of regions with varying vulnerability levels. This visualization helps pinpoint areas where socio-economic factors intersect with environmental stressors, influencing communities' capacity to adapt to coral reef degradation. Understanding social vulnerability is essential for targeted interventions and adaptive strategies to enhance coastal communities' resilience and promote sustainable reef management.

The choropleth maps provide a spatial representation of different variables related to coral reefs, allowing for quick visual comparisons and identification of regions with specific characteristics or vulnerabilities. These visualizations can assist in prioritizing conservation efforts, resource allocation, and the development of adaptive strategies for coral reef management and protection.

5.3 Shiny App with Interactive Map

The world map with circular markers representing different regions or countries. The size of the markers appears to be proportional to the Social Vulnerability Index value for that region. The map uses a colour scale ranging from yellow (low vulnerability) to dark red (very high vulnerability) to differentiate the markers based on their vulnerability category. A zoomed-in view of the interactive map, focusing on a specific region. It provides more detailed information about individual countries or regions. When a specific marker is hovered over or clicked, a popup appears displaying additional data, such as the country name, Reef Dependence Index, Adaptive Capacity Index, and Social Vulnerability Index.

The interactive map visualizes the social vulnerability of regions or countries concerning coral reefs, indicating their susceptibility to ecosystem changes or threats. Areas with higher social vulnerability are more likely to suffer from coral reef degradation, impacting livelihoods and food security. By enabling users to explore and adjust the Social Vulnerability Index range, the visualization aids in identifying areas requiring targeted intervention or adaptation strategies. Moreover, by incorporating related indices like Reef Dependence and Adaptive Capacity, it offers a comprehensive understanding of factors influencing vulnerability to coral reef-related issues. This tool empowers researchers, policymakers, and stakeholders to prioritize efforts in coral reef conservation and management effectively.

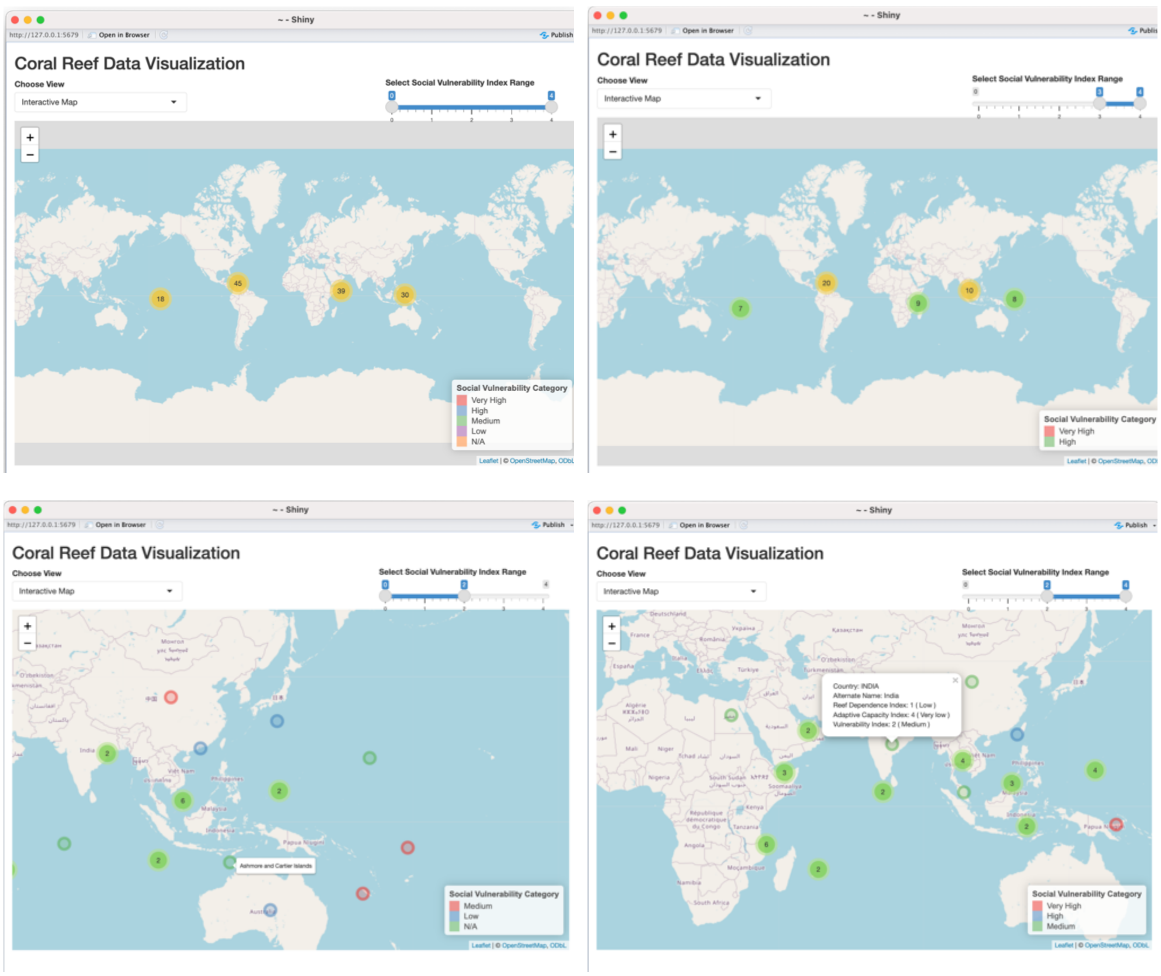

Figure 3 Interactive Map

5.4 Heatmap for Coral Bleaching Alert Areas (CRW_BAA)

This heatmap shows coral bleaching alert zones in various geographies. The colour scale runs from purple to yellow, with purple signifying the highest warning level for coral bleaching and yellow being the lowest alert level. Significant coral bleaching alerts are shown in purple and blue, while yellow and green patches represent locations with moderate to low alert levels. The caption on the right side gives guidance for interpreting the colour scale, with higher values indicating more severe coral bleaching alerts. Overall, this visualisation depicts the spatial distribution and intensity of coral bleaching episodes in various geographic regions, which might be caused by rising ocean temperatures or other environmental stresses that affect coral reef ecosystems. The visualization provides insight into the spatial distribution and intensity of coral bleaching episodes.

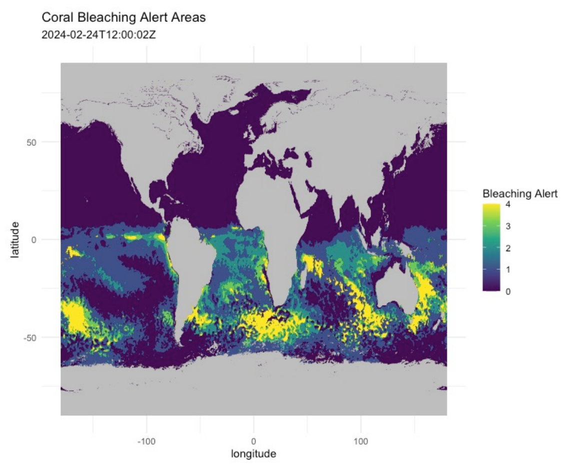

Figure 4: Heatmap for Coral Bleaching Alert Areas

5.5 Bleaching Alert Area 7-day Maximum Composite

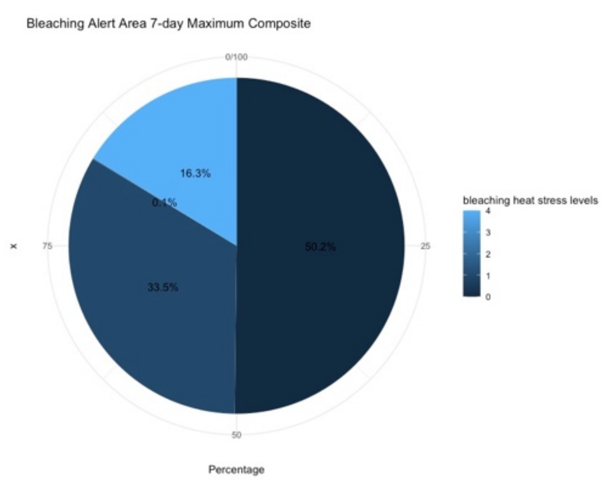

Figure 5: Bleaching Alert Area 7-day Maximum Composite

The pie chart illustrates the proportion of each category of bleaching heat stress levels over a 7-day maximum composite period. The use of a pie chart is beneficial when one wants to depict parts of a whole and it is especially effective for showing relative sizes at a glance. This is valuable for quickly conveying how bleaching events are distributed across different stress levels. From the results shown in the pie chart, we can infer that the largest segment (over 50%) represents one category, which could possibly be the least severe stress level. The remaining segments represent the other levels, with the smallest one being just 0.1%. This distribution helps to understand which bleaching heat stress levels are most common.

5.6 Distribution of sea surface temperature (CRW_SST) and anomalies (CRW_SSTANOMALY)

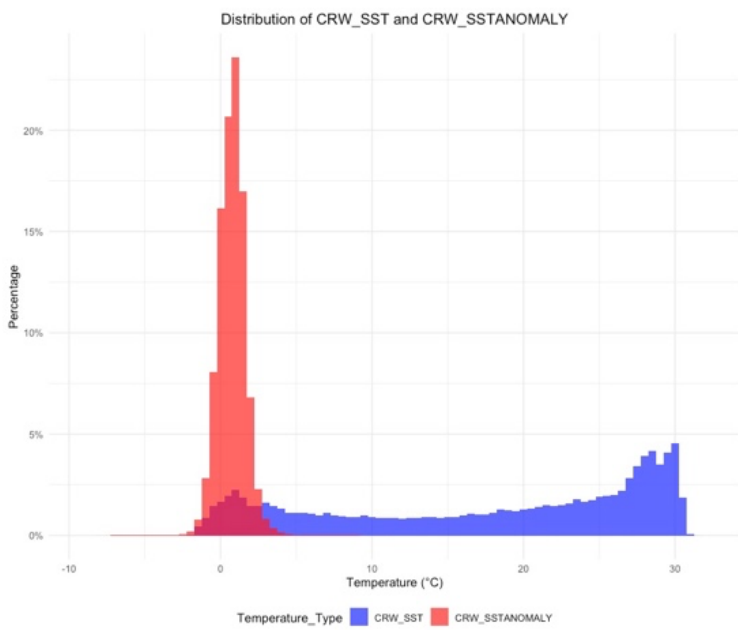

Figure 6: Distribution of sea surface temperature (CRW_SST) and anomalies (CRW_SSTANOMALY)

The rationale for drawing this graph is to compare the distributions of actual sea surface temperatures with their anomalies. This is important for understanding the typical range of temperatures and identifying how far and in what manner the anomalies deviate from the expected values. Such information is crucial for studying climate change effects on marine ecosystems, especially coral reefs which are sensitive to temperature changes.

The result of the graph shows a distribution for sea surface temperatures predominantly in the positive range, peaking around a certain temperature which appears to be the mode of SST values. On the other hand, the temperature anomaly distribution has a significant peak at around zero, suggesting that many of the anomalies are small or negligible. However, there are also tails extending into both the positive and negative ranges, indicating instances of significant positive and negative deviations from the norm. The blue bars represent the CRW_SST and the red bars represent the CRW_SSTANOMALY. The distinct peak in the SST distribution suggests a common range of temperatures most frequently observed, whereas the spread in the anomaly distribution indicates variability in how much temperatures deviate from an established baseline or average.

6 EVALUATION

The Coral Reef Data Visualisation is intended to rapidly handle and show complex geographical and environmental data relevant to coral bleaching occurrences. The system makes use of strong R packages such as sf for spatial data management, ggplot2 for high-quality visualisations, and shine for developing an intuitive user interface. One of the system's primary characteristics is its ability to produce a variety of visualisations, such as heatmaps, pie charts, histograms, and interactive bubble charts, with minimum user input. This feature simplifies the visualisation process by allowing users to easily explore and analyse data from several angles.

In terms of performance, the system is extremely efficient at data loading and pre-processing, ensuring that raw data is converted into acceptable forms for visualisation in a timely way. The usage of optimised libraries and algorithms improves overall responsiveness and the user experience. According to informal observations, the average time spent creating a visualisation using the technology is short. This might be due to the well-designed user interface, which allows users to effortlessly navigate between visualisation components.

The visualizations' focus on accessibility is laudable, since it uses the viridis colour palette for heatmaps, guaranteeing that the visualisations are visible to people with colour vision problems. Additionally, pie charts and histograms are displayed with unambiguous percentages and distributions, which improves interpretability. Interactive visualisations, such as bubble charts built with the plotly package, provide dynamic user engagement by allowing users to explore multiple indices and data points by direct interaction with plot components. Furthermore, the usage of the leaflet package for geographic data visualisation allows users to interact with geographical distributions in a meaningful and straightforward way.

7 DISCUSSION

The Coral Reef Data Visualization has provided valuable insights into the current state of coral reef habitats worldwide and the potential impact of their degradation on nations and territories that rely on these ecosystems. Through the comprehensive analysis and intuitive visualizations, the audience has gained a deeper understanding of the socioeconomic vulnerabilities associated with reef loss, as well as the ability of different regions to resist and adapt to these changes.

One of the significant contributions of this work is the identification of regions that are highly sensitive to coral bleaching events. By highlighting these areas, the system has enabled conservation efforts to be targeted and prioritized, ensuring that resources are allocated effectively to address the most pressing issues. Additionally, the visualizations have provided a clear depiction of the extent of human activities, such as pollution, overfishing, and destructive fishing practices, that threaten coral reef ecosystems, raising awareness and underscoring the urgency for action.

The visualizations' ability to integrate diverse data sources, including environmental factors, socioeconomic indicators, and geographic information, has facilitated a holistic understanding of the complex interplay between coral reef health and human communities. This comprehensive approach has allowed for the identification of potential hotspots where conservation efforts may yield the greatest impact, not only in preserving the reefs but also in safeguarding the livelihoods and well-being of local populations.

Furthermore, the system has enabled the exploration of potential management strategies and conservation measures tailored to specific regions or reef systems. By integrating socioeconomic factors and considering the adaptive capacity of different nations and territories, the visualizations have provided a framework for developing sustainable and culturally appropriate solutions that consider the needs and vulnerabilities of local communities.

Overall, the Coral Reef Data Visualization has proven to be a powerful tool in raising awareness, facilitating informed decision-making, and fostering collaborative efforts toward the protection and preservation of coral reef ecosystems worldwide. The insights gained from this work have the potential to mobilize targeted conservation initiatives, promote sustainable practices, and ultimately contribute to the resilience and continuity of these vital marine habitats and the communities they support.

8 CONCLUSION AND FUTURE WORKS

The Coral Reef Data Visualization has proven to be a valuable tool in addressing the pressing issues faced by coral reef ecosystems worldwide. Through its comprehensive analysis and intuitive visualizations, it has provided insights into the current state of these habitats, identified regions of high sensitivity to coral bleaching, and offered actionable information for conservation and management initiatives.

One of the key takeaways from this work is the importance of adopting a holistic approach to understanding and addressing the threats to coral reefs. By integrating diverse data sources, including environmental factors, socioeconomic indicators, and geographic information, the system has highlighted the complex interplay between coral reef health and human communities. This comprehensive perspective has allowed for the identification of potential hotspots where conservation efforts can yield the greatest impact, not only in preserving the reefs but also in safeguarding the livelihoods and well-being of local populations.

Additionally, the visualizations have demonstrated the value of effective data visualization in communicating complex information to a wide range of stakeholders, including researchers, policymakers, and local communities. The intuitive user interface and interactive features have facilitated engagement with the data, fostering a deeper understanding of the significance of coral reef ecosystems and the urgency of addressing the threats they face.

Moving forward, there are several avenues for extending and refining the Coral Reef Data Visualization System to further enhance its impact and reach:

1. Expand data sources and integration: Continuously expanding the range of data sources and improving data integration will provide a more comprehensive picture of the factors influencing coral reef health. This could include incorporating additional environmental data, such as ocean acidification levels, as well as socioeconomic factors like tourism and fishing practices.
2. Develop predictive models and forecasting capabilities: By leveraging machine learning and advanced modelling techniques, the system could incorporate predictive capabilities to forecast future coral bleaching events, enabling proactive conservation measures and early warning systems.
3. Enhance user engagement and collaboration: Exploring opportunities for citizen science and community engagement could broaden the reach and impact of the system. By involving local communities in data collection and monitoring efforts, the system could foster a sense of ownership and encourage grassroots conservation initiatives.
4. Integrate decision support tools: Developing decision support tools within the system could assist policymakers and conservation organizations in evaluating the effectiveness of proposed management strategies and conservation measures. This could involve scenario analysis, cost-benefit analysis, and the consideration of socioeconomic factors.
5. Improve accessibility and localization: Ensuring that the system is accessible to users with varying levels of technical expertise and in different languages could increase its reach and impact, particularly in regions where coral reefs are a critical resource.

6. Foster collaboration and knowledge sharing: Establishing partnerships and collaborations with research institutions, non-governmental organizations, and local communities could facilitate the exchange of knowledge and best practices, ultimately enhancing the effectiveness of conservation efforts.

By continuously refining and expanding the Coral Reef Data Visualization System, we can contribute to the development of targeted conservation strategies, promote sustainable practices, and foster a collaborative approach to preserving these vital marine habitats and the communities they support.

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A APPENDICES

A.1 Data structure of the spatial data `shape_data`

Table 1: Data structure of the spatial data `shape_data`

Variable Name	Data Type	Description
COUNTRY	String	The name of the country or territory associated with the coral reef data.
Alt_Name	String	An alternative name or abbreviation for the country or territory.
R_Dep_Indx	Float	A numerical value representing the extent of the country's dependence on coral reefs, calculated from various socio-economic factors like reef-associated population and fisheries.
R_Dep_Cat	String	The classification of the Reef Dependence Index into quartiles (low, medium, high, very high), categorizing the level of dependence each country has on coral reefs.
Adapt_Indx	Float	A numerical score assessing the country's ability to adapt to changes or threats to coral reefs, based on factors like economic resources and governance.
Adapt_Cat	String	The classification of the Adaptive Capacity Index into quartiles (very low, low, medium, high), categorizing the ability of a country to adapt to coral reef changes.
Vuln_Indx	Float	A numerical value derived from combining the Reef Dependence Index, Adaptive Capacity Index, and exposure to reef threats, indicating the overall social vulnerability of the country to coral reef degradation.
Vuln_Cat	String	The classification of the Social Vulnerability Index into quartiles, ranking countries based on their vulnerability to the impacts on coral reefs.
Notes	String	Any additional information, comments, or relevant notes about the data for each country.
geometry	Geometry	The spatial data associated with each country, typically represented as polygons in a GIS format (e.g., MULTIPOLYGON in this case), containing the location and boundaries of the country.

[a] Note that the `geometry` column is of the `Geometry` data type, which is a specific data type used to store spatial data in GIS systems. The geometry type `MULTIPOLYGON` indicates that the spatial data for each country is represented as a collection of polygons, which can be used to display the country's boundaries on a map.

A.2 Data structure of CSV file NOAA coral reef data `coral_data`

Table 2: Data structure of CSV file NOAA coral reef data `coral_data`

Variable Name	Data Type	Description
time	Float	2024-02-24T12:00:00Z
latitude	Float	The latitude coordinate in degrees north.
longitude	Float	The longitude coordinate in degrees east.
CRW_BAA	Integer	The bleaching alert area, indicating the level of coral bleaching heat stress (0 - No Stress, 1 - Bleaching Watch, 2 - Bleaching Warning, 3 - Bleaching Alert Level 1, 4 - Bleaching Alert Level 2).
CRW_BAA_mask	Integer	A flag array that classifies land, missing, and ice pixels for CRW_BAA data.
CRW_BAA_7D_MAX	Integer	The 7-day maximum composite of the bleaching alert area.
CRW_BAA_7D_MAX_mask	Integer	A flag array that classifies land, missing, and ice pixels for CRW_BAA_7D_MAX data.
CRW_DHW	Float	The degree of heating week, a measure of thermal stress on coral reefs.
CRW_DHW_mask	Integer	A flag array that classifies land, missing, and ice pixels for CRW_DHW data.
CRW_HOTSPOT	Float	The coral bleaching hotspot, indicating areas with higher-than-average sea temperatures.
CRW_HOTSPOT_mask	Integer	A flag array that classifies land, missing, and ice pixels for CRW_HOTSPOT data.
CRW_SEAICE	Float	The sea ice fraction.

Variable Name	Data Type	Description
CRW_SST	Float	The sea surface temperature.
CRW_SSTANOMALY	Float	The sea surface temperature anomaly.
CRW_SSTANOMALY_mask	Integer	A flag array that classifies land, missing, and ice pixels for CRW_SSTANOMALY data.

[a] the `_mask` variables are typically used to filter or mask out certain data points based on specific conditions (e.g., land, missing, or ice pixels).