

Chapter 12

Mapping Multi-decadal Mangrove Forest Change in the Philippines: Vegetation Extent and Impacts of Anthropogenic and Climate-Related Factors



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Abstract There is a continuous decline of mangrove forests in the Philippines due to anthropogenic activities and natural disturbances. Through the years, monitoring of mangrove extent was done as part of the many local efforts to manage mangrove forests. However, existing mangrove cover estimates were generated by varied sources with different methodologies and classification techniques. This study aims to utilize a standardized method to detect multi-decadal spatio-temporal mangrove extent with the use of Landsat-derived Mangrove Vegetation Index (MVI) calculated in Google Earth Engine (GEE). Mangroves were mapped per region and areal changes were calculated from the period 2000 to 2020. A decline of 29,000 hectares was recorded from 2000 to 2020, observed in 12 out of the 17 Philippine administrative regions. The variations in rainfall, typhoons, sea surface height, temperature, and occurrence of land use/cover conversion were seen to have impacted the structure and extent of mangrove communities. Results show that higher multi-decadal mangrove losses were observed in regions with higher precipitation change ($r = 0.68$ to 0.99), higher maximum sea surface temperature ($r = 0.39$), more frequent typhoons ($r = 0.43$), and those exposed to extreme heating ($r = 0.47$) and precipitation events ($r = 0.51$). Areas that were least devastated by typhoons (fewer than 10 typhoons) have recorded increased vegetation cover such as in Northern Mindanao (Region 10), Autonomous Region in Muslim Mindanao (ARMM), and Zamboanga

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W. Leal Filho et al. (eds.), *Climate Change Strategies: Handling the Challenges of Adapting to a Changing Climate*, Climate Change Management,
https://doi.org/10.1007/978-3-031-28728-2_12

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Peninsula (Region 9). Reduction in precipitation can increase salinity which lowers seedling survival, growth rates, and productivity; while the impact of typhoons is mainly attributed to physical damages brought by strong waves and wind. Some of the previous mangrove areas were found to be converted to fishponds and built-up areas brought by the increasing demands for the economical use and development of land. Understanding the impacts of these natural and human-induced drivers will aid in formulating effective conservation and resource management measures. Further, the proposed standardized mapping workflow allowed detailed analysis of these impacts as reflected by the spatio-temporal changes in mangrove extent.

Introduction

There is a continuous decline of mangrove forests in the Philippines due to climate-related factors and anthropogenic activities. The human-induced factors include mainly conversion to aquaculture, urban development, large scale deforestation, and lack of coastal protection measures. The decline of Philippine mangroves from 1950 to 1970s was largely attributed to the conversion to fishponds, and these were well documented (Primavera 1995, 2000). It was only on the later part of the 1970s that the national government fully understood the economic and environmental importance of mangroves. Since then, various programs and policy initiatives were undertaken to recover the damages brought by land use conversion.

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Meanwhile, climate-induced factors such as climate variability were reported to greatly impact the species composition, adaptation to salinity, survival rate, and productivity of mangroves around the world (Ghosh et al. 2017). Among the factors that can influence mangrove forests, multiple studies highlighted the effects of climatic variables such as changes in temperature, rainfall variation, sea-level rise, frequency of typhoons, high water events, and concentration of atmospheric gases (Alongi 2015; Duke et al. 1998; Ghosh et al. 2017; Willard and Bernhardt 2011). Changes in the level of these variables are associated with climate change as continued global warming intensifies global water cycle, monsoon precipitation, and the severity of extreme events (IPCC 2021). The effect of typhoons to mangroves is an area of interest because the country is a known gateway for tropical cyclones coming from the Pacific Ocean. Annually, there are around 20 tropical cyclones that enter the Philippine Area of Responsibility (PAR) including typhoons like Haiyan, one of the strongest typhoons that devastated the country in 2013 which has caused damage to the mangrove forests within and near its track (Buitre et al. 2019).

The impacts of climate-related and human-induced factors to mangrove forest can be known by analyzing the trend or changes in the area or extent. Mangrove extent statistics can be compared through the use of historical and recent mangrove extent data. In the country, varying trends of mangrove area were observed throughout the decades. Larger mangrove areas were reported in earlier years between 1918 (450,000 Ha) to 1968 (448,310) with field estimates reported by then Philippine Council for Agriculture, Forestry and Natural Resources Research and Development and L.M. Lawas, respectively. Relatively smaller yearly estimates were reported by the Bureau of Forest Development (now the Forest Management Bureau) from 1969 to 1984 (295,190–233,514 Ha). From year 1990 onwards, a significant shift from field-based mapping to Remote Sensing-based (RS) approaches was observed in the Philippines, providing more rapid and less expensive approach. These includes the estimates of Long and Giri (2011), Long et al. (2014), NAMRIA (every 5 years), and Global Mangrove Watch (Bunting et al. 2018). These mangrove cover estimates have different levels of accuracy based on factors such as the spatial and temporal resolutions of the satellite images, image classification technique, and the quality and quantity of ground validation data.

Despite the existing methodologies in mangrove extent mapping, a standardized mangrove mapping workflow is still needed to accurately detect the impacts of climate and human-induced drivers to mangrove forest's extent. For example, the estimates accounted for Philippine mangroves were obtained from different institutions and resources which utilized different methods, satellite data, and validation protocols. Comparing statistics among these different sources may not actually capture the actual trend of local areal changes. To solve this, new methodologies were being developed including novel methodologies for rapid extent estimation using mangrove indices. The Mangrove Vegetation Index (MVI) was proposed by Baloloy et al. (2020) to rapidly classify mangrove cover and separate the same from non-mangrove classes such as bare soil, built-up, terrestrial forests, grassland, clouds, and water. MVI measures the probability of a pixel to be a 'mangrove' by extracting the greenness and moisture information from the green, NIR, and SWIR satellite

image bands. The range of MVI values may vary depending on factors such as land cover classes, climatic conditions, or tidal conditions. MVI was previously utilized to map the 2019 mangrove extent of the Philippines using Sentinel-2 data (Baloloy et al. 2020). The application of MVI for historical mapping using Landsat imagery offers opportunity for an accurate, long-term analysis of mangrove trends and in detecting the potential contribution or effect of climate and human-induced factors to the decadal changes in extent.

This study aims to utilize a satellite remote sensing method to detect multi-decadal spatio-temporal mangrove extent (2000–2020) in the Philippines with the use of Landsat-derived MVI. Decadal values of factors that may affect mangrove extent will be obtained, including the following variables: rainfall, sea surface temperature (SST), sea surface height (SSH), number of typhoons, air-sea climate exposures, and LULC changes. These environmental and climate-related factors will be correlated with the decadal mangrove statistics to determine their respective impacts. Understanding the effect of these drivers will aid in formulating effective conservation and resource management measures.

The mangrove extent estimates calculated in this study were derived from Landsat data with no ground validation conducted. The mapping method adapted, however, was previously applied in Sentinel-2-based mangrove mapping in the Philippines with high accuracy results. The study period is limited between years 2000 and 2020 only, thus discussions on pre-2000 mangrove estimates and land cover conversion activities were based on published references. Moreover, only major climate-related factors were considered in this study, selected based on their reported impacts to vegetation health and the availability of local data with long temporal records. The variables presented here are also the major climatic variables highlighted in the IPCC 2021 report with a global concern: sea surface temperature, precipitation, sea level rise, and the occurrence of tropical cyclones and other extreme weather events.

Materials and Methods

The information needed to assess the impacts of human-induced and climate-related factors to mangrove extent are divided mainly of two categories. Firstly, historical mangrove extents were generated (2000–2020) as the main indicators of the impacts from the environmental variables. This mangrove extents were obtained using Remote Sensing data and techniques, with Landsat as the main satellite data source. Novel methodologies (e.g., MVI-based mapping) and platforms such as Google Earth Engine were utilized to hasten the generation of a mangrove extent data. The second main data needed is the collated climate-related and human induced factors. Among the many variables that may affect the extent and health of mangrove forests, significant variables were selected based on previous related studies (Alongi 2015; Buitre et al. 2019; Duke et al. 1998; Friess et al. 2012; Ghosh et al. 2017; Krauss et al. 2014; Willard and Bernhardt 2011; Ximenes et al. 2016).

Mangrove Extent Mapping

Multi-decadal mangrove maps of the Philippines (2000, 2010, and 2020) were generated using the MVI formula implemented in GEE (Fig. 12.1). Atmospherically corrected Sentinel-2 images were downloaded and used to generate the MVI raster layers based on the identified optimal minimum threshold and a fixed maximum threshold of 20. MVI is a new simplified index for fast and accurate mapping of mangrove extent from remotely-sensed images. The Mangrove Vegetation Index (MVI) equation is in the form:

$$\text{MVI} = (\text{NIR} - \text{Green}) / (\text{SWIR1} - \text{Green}) \quad (12.1)$$

where NIR, Green, and SWIR1 are the near-infrared, green, and shortwave infrared-1 reflectance values. The $|\text{NIR} - \text{Green}|$ enhances the differences of vegetation greenness between mangrove pixels and other vegetation, while $|\text{SWIR1} - \text{Green}|$ captures the distinct moisture of mangrove pixels compared to non-mangrove pixels. In this study, the equivalent bands in Landsat 8, 7, and 5 were utilized. The example formula for Landsat-8 MVI (Eq. 12.2) is written as:

$$\text{Landsat-8 MVI} = (\text{B8} - \text{B3}) / (\text{B6} - \text{B3}) \quad (12.2)$$

where Bands 3, 5, and 6 are the equivalent green, NIR and SWIR1 bands in Landsat-8, respectively.

Generation of MVI layer, threshold selection, and quality-checking were all implemented in GEE. GEE is a powerful web-platform for cloud-based processing of remote sensing data on large scales, providing a variety of constantly updated data sets, thus no download of raw imagery is required. The study specifically utilized Code Editor, a web-based integrated development environment (IDE) which can be accessed at: <https://code.earthengine.google.com>. After generating the MVI layers, outputs were exported as a raster file for data cleaning and area calculation in ArcGIS™. Cleaning of noise pixels was done by overlaying the MVI raster on the false color composite display of Sentinel-2 image (RGB: B11-B8-B4).

The annual mangrove map statistics was calculated per Philippine administrative region as shown in Fig. 12.2. The country has a total of 17 regions, but only 16 were used in this study excluding the Cordillera Administrative Region (CAR)



Fig. 12.1 Summary of the workflow for generating the decadal mangrove maps and statistics. More detailed information on MVI-based mapping was described in Baloloy et al. (2020). Here, the MVI was first applied to Sentinel-2 imageries to map the 2019 mangrove extent in the Philippines

since the region is in higher elevation areas with no mangrove forest in its administrative boundary. Re-calculation of mangrove statistics per region was implemented in ArcGIS™ with the zonal statistics tool. The region shapefile was obtained from the National Mapping and Resource Information Authority (NAMRIA). In addition, decadal statistics on the nationwide constant mangrove cover, cover gain, and cover lost were mapped and calculated.

Climate-Related Variables

There were five selected climate-related or climate-induced variables considered in this study namely annual rainfall, sea surface temperature (SST), sea surface height (SSH), typhoon data, and air-sea climate exposure.

The annual rainfall data was obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), a 35+ year quasi-global rainfall data set. CHIRPS is produced at 0.05×0.05 degree spatial resolution. The CHIRPS dataset was developed on previous approaches to smart interpolation techniques and high-resolution precipitation estimates based on infrared Cold Cloud Duration datasets (Funk et al. 2015). Satellite information were incorporated in the CHIRPS data in three ways: by producing high resolution precipitation climatologies from satellite; by using CCD fields to estimate monthly and pentadal precipitation anomalies; and by using satellite precipitation fields to estimate local distance decay functions (Funk et al. 2015). The CHIRPS data was utilized by significant number of studies on climate and rainfall trend modelling (Beck et al. 2017; Mu et al. 2021) while some studies were conducted to validate this dataset (Shrestha et al. 2017; Rivera et al. 2018). The rainfall data for years 2000–2020 was downloaded and accessed from CHIRPS website: <https://www.chc.ucsb.edu/data/chirps>.

The sea surface height dataset used are actual measurement from tide gauges in the country, acquired from NAMRIA and processed in text file format. One tide gauge station per region was selected. Correction was applied to reference the height data with the WGS84 ellipsoid. Meanwhile, Group for High Resolution Sea Surface Temperature (GHRSSST) Level 4 sea surface temperature dataset was used in determining the effect of SST to the mangrove extent decadal trend. GHRSSST is an analysis based upon nighttime GHRSSST L2P skin and subskin SST observations from several instruments (e.g., AMSR-E, MODIS, AVHRR). This dataset was widely used as a validation data to other satellite-derived SSTs such as those derived from Landsat (Donlon et al. 2007; Jang and Park 2019). High-resolution SST analysis based on GHRSSST SSTs have been adopted internationally by operational agencies. For this study, the dataset was obtained from the Physical Oceanography Distributed Archive Center (PODAAC) of NASA's Jet Propulsion Laboratory: <https://podaac.jpl.nasa.gov/>. The downloaded grids are those within or nearest the tide gauges stations in the respective Philippine administrative regions. The available dataset is from year 2003 to 2020.

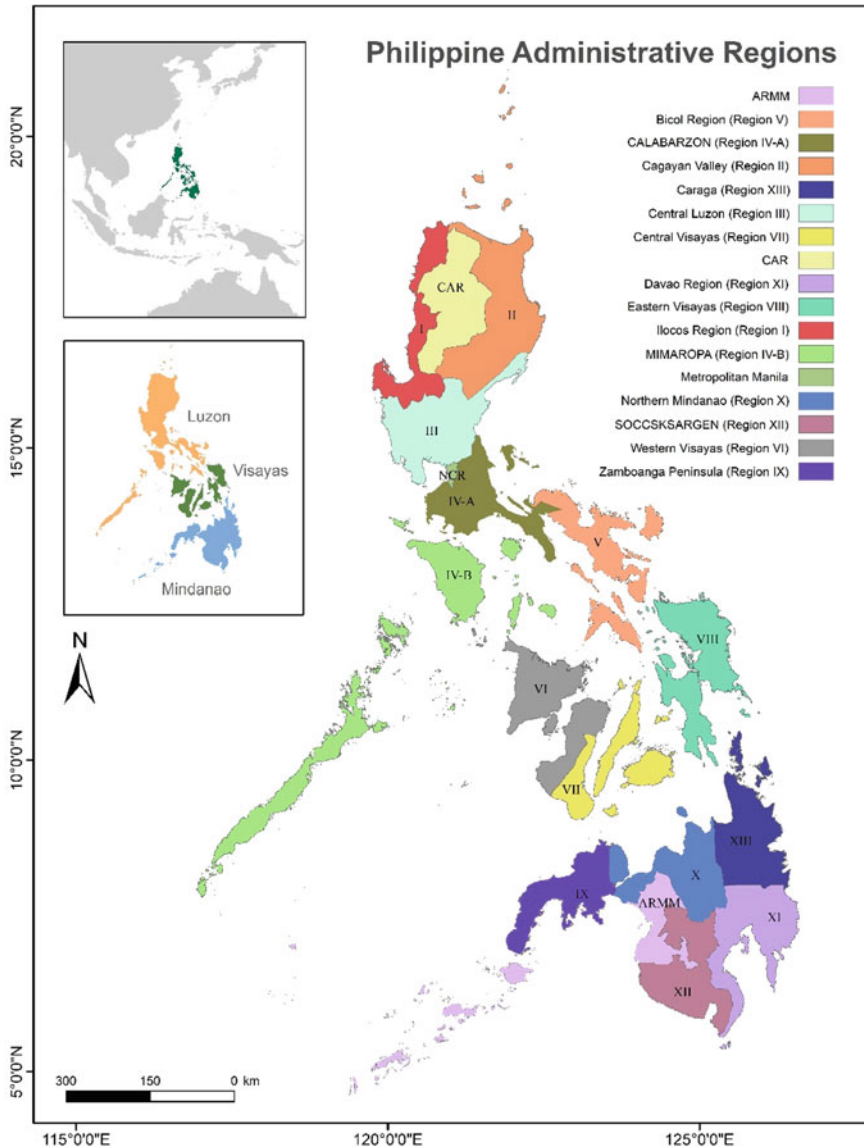


Fig. 12.2 The Philippine administrative regions used as the smallest unit for mangrove extent comparison between regions and between decades. Administrative regions are composed of provinces and/or independent cities. Philippines has three main island groups: Luzon, Visayas, and Mindanao (lower left inset), consists of varying number of administrative regions. The climate-related factor variables were also collated by region to facilitate comparison with the mangrove statistics. Analysis and presentation of results were discussed using this unit

Typhoon track data was obtained from NOAA International Best Track Archive for Climate Stewardship (IBTrACS), filtered from 1999 to 2019 (Knapp et al. 2018). IBTrACS project is the most complete global collection of tropical cyclones available wherein recent and historical tropical cyclone data from multiple agencies were collated and released publicly. IBTrACS was developed through a collaboration with all the World Meteorological Organization (WMO) Regional Specialized Meteorological Centers around the world (Knapp et al. 2010, 2018). From this dataset, only typhoon track and typhoon count can be obtained; data on the typhoon strength or intensity are not included. The climatologies and counts are based solely on wind speed. For this study, the tracks were filtered using the national administrative boundary and typhoon counts were calculated per administrative regions from year 1999 to 2019.

Data on the Philippine air-sea climate exposures, namely, sea surface temperature (SST), sea surface height (SSH), and rainfall (David et al. 2015), were added as important variables in this study. David et al. (2015) utilized remote sensing data to categorize the archipelagic waters of the Philippines into distinct clusters of historical air-sea climate exposures. The trends and anomalies of SST, precipitation, and SSH were calculated within each cluster. The statistics were then compared amongst the clusters and against global statistics (David et al. 2015). This secondary dataset is a significant variable in understanding the impact of this natural air-sea climate exposure to the changes in our mangrove forests.

Human-Induced Variables

The change in specific land cover type per region is the main indicator used in detecting the impacts of anthropogenic activities to mangrove extent. Specifically, the total area of converted mangrove cover to fishponds and built-up structures were utilized as the anthropogenic variable metrics.

For this analysis, the NAMRIA land cover data for years 2006 and 2015 (Fig. 12.3) were used. The fishponds and built-up shapefile for year 2015 were clipped with the 2006 mangrove shapefile to identify the areas that were previously detected with mangrove cover.

Variable Metrics and Regression

The five selected variables (rainfall, typhoon count, SST, SSH, and air-sea climate exposure) can signify different impacts to mangrove extent based on the temporal and spatial aggregation of their statistics. To simplify and focus the analysis, only significant variable metrics were utilized to later regress with the decadal mangrove extent data. These metrics are shown in Table 12.1.

2015 LAND COVER

- Annual Crop
- Brush/Shrubs
- Built-up
- Closed Forest
- Fishpond
- Grassland
- Inland Water
- Mangrove Forest
- Marshland/Swamp
- Open Forest
- Open/Barren
- Perennial Crop
- Unclassified

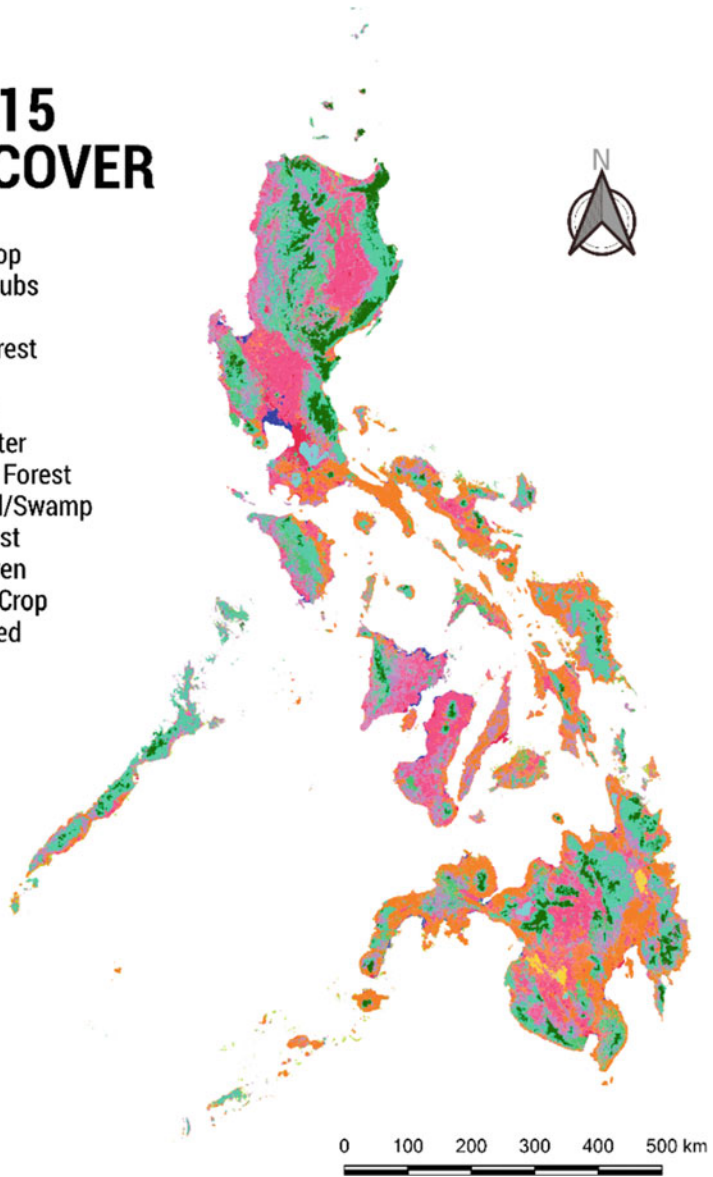


Fig. 12.3 The 2015 Land Cover Map of the Philippines from NAMRIA, the central mapping agency of the Philippine government. The 12 land cover classes were derived from Landsat-8 images processed in e-Cognition software for image segmentation techniques

Table 12.1 Specific metrics used for the environmental and human-induced factors. Selection of variables and metrics were guided by published reports on climate change and the corresponding impacts on mangrove forests. Availability of local and remotely-sensed data were also considered

Environmental factors	Metrics	Time frame
Rainfall (mm)	Decadal total rainfall	2000–2020
	Mean annual rainfall	
	Mean annual rainfall increment/region	
	Mean annual rainfall increment/climate type	
Sea surface temperature (°C)	Mean SST difference	2003–2020
	Average annual minimum SST	
	Average annual max SST	
Typhoon	Total typhoon count	1999–2019
Tide gauge sea surface height (m)	Sea surface height difference	2000, 2012–2019
Historical air-sea climate exposure	Extreme heating events	1982–2008
	Extreme precipitation	1998–2009
	Precipitation changes	1998–2009
	Sea level rise	1992–2008
Land cover conversion	Mangroves area converted to built-up and fishponds (Ha)	2000–2015

The metrics were computed from the pre-processed data on rainfall, SST, SSH, typhoon tracks, and air-sea climate exposure. The time frame differed between the variables depending on the earliest and the latest available dataset. However, all data fall within the decal observation period which is from year 2000 to 2020. Mean annual rainfall was calculated by computing the decadal mean of the annual total rainfall within the observation period. Meanwhile, total rainfall is the decadal total amount of rainfall received by each region. Rainfall increment refers to the lost or gained values in the amount of rainfall every other year, or simply the difference in rainfall between succeeding years. Minimum and maximum SST were calculated by getting the minimum and maximum recorded daily values throughout the year, respectively. Mean SST difference is the difference between the earliest and the latest observation data on SST. SSH difference was obtained by calculating the difference in tide gauge-measured data for years 2019, 2012, and 2000. The metrics utilized for the historical air-sea climate exposures were the parameters regressed with remote sensing data.

Data correlation was done through linear regression as applied to the mangrove extent and environmental variables. Variables such as rainfall and SST include all available annual data between the observation period and not only for the earliest (2000) and latest year (2020). For the air-sea climate exposure, the data used was

already processed by the primary source (David et al. 2015) and is ready for correlation between the mangrove extent data. This dataset only covered the years 1992–2009, or half of the study period considered in this study. Thus, one limitation in adopting.

This dataset for correlation with mangrove trend is the assumed linear behavior of the climate-related hazards after year 2009. All correlations were made between datasets aggregated to regional levels, while additional correlation was done between mangrove extent and rainfall increment per climate type. This was carried by identifying first the dominant climate type category of each region and grouping all regions belonging to the same category.

Decadal Mangrove Trend in the Philippines

Maps and Statistics

Mangrove extent maps and statistics were generated for years 2000, 2010, and 2020 (Fig. 12.4). Varying trends were observed wherein the mangrove extent is highest in 2000 (294,026 Ha), followed by 2020 (264,818 Ha), and lowest in 2010 (230,597 Ha).

By comparing maps on a national scale, only the general trend could be observed. There are variations on the level of extent gain or loss through data aggregation by administrative regions, which will be correlated later with the respective human-induced and climate-related variables. Regional statistics showed that in most regions, the highest mangrove areas were recorded in 2000, most declined in 2010, and either increased or decreased in 2020 (Fig. 12.5). Consistently higher

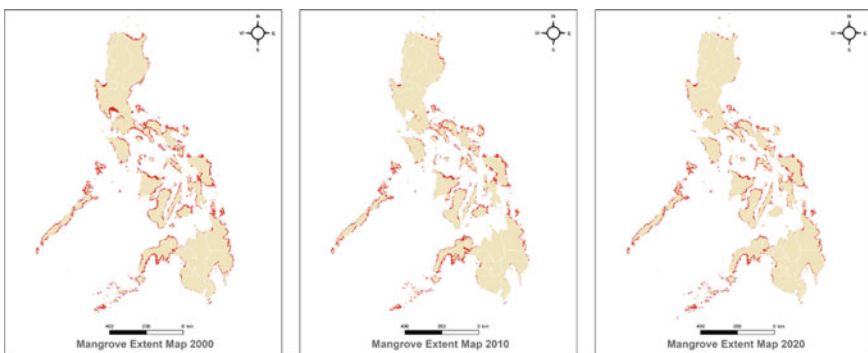


Fig. 12.4 Decadal mangrove extent map of the Philippines for years 2000, 2010, and 2020. Minimal changes can be observed graphically due to the presence of constant mangroves and those areas with varying trend. Similar mangrove locations can be instantly observed among the three decadal extents

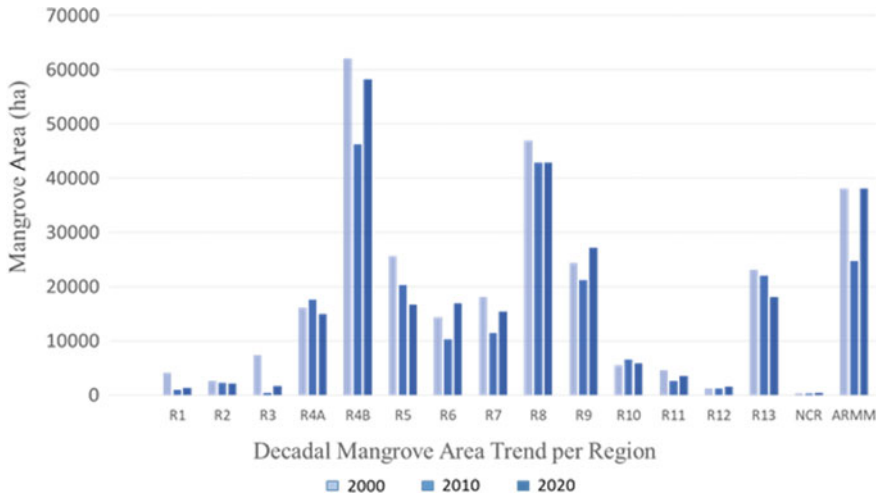


Fig. 12.5 Decadal mangrove extent regional statistics of the Philippines for year 2000, 2010, and 2020

estimates were recorded in Region 4B (MIMAROPA), Region 8 (Eastern Visayas), Region 9 (Zamboanga Peninsula), and the Autonomous Region in Muslim Mindanao (ARMM). These regions are located in the Visayas and Mindanao islands. Few mangroves are located in regions within Luzon such as Region 1 (Ilocos region), Region 2 (Cagayan Valley), and Region 3 (Central Luzon). A decline of 29,000 hectares was recorded from 2000 to 2020, and the declining trend was observed in 12 out of the 17 Philippine administrative regions. From these observations, we can say that the general trend of the mangroves in the country is still decreasing.

In addition to the decadal map, cover maps of the gained, loss, or retained mangroves were generated (Figs. 12.6 and 12.7). These maps show if the changes in mangrove forests took place within the same area or coverage, or if there are new areas where mangroves have grown or extended. Based on these maps (Figs. 12.6 and 12.7), mangrove cover gains were observed within or near existing mangrove areas signifying expansion from its previous extent. Meanwhile, cover losses were pronounced only in some regions, such as Eastern Visayas and Bicol Region, where variations maybe attributed to the human-induced and climate-related variables being considered in this study. The distribution of retained mangrove cover (Fig. 12.7) shows that most mangrove forests in the country can still thrive and recover especially those located within dense forests such as in Palawan (in Region IV-B) and Siargao (in Region XIII).

The application of MVI was considered helpful in generating the mangrove extent maps following a standardized index-based method. Based on quality-checking outputs, there are aquaculture areas misclassified as mangroves in previous mangrove maps in the country (Long and Giri 2011). In this study, the MVI has separated mangroves from non-mangrove areas, although further validation activities are still

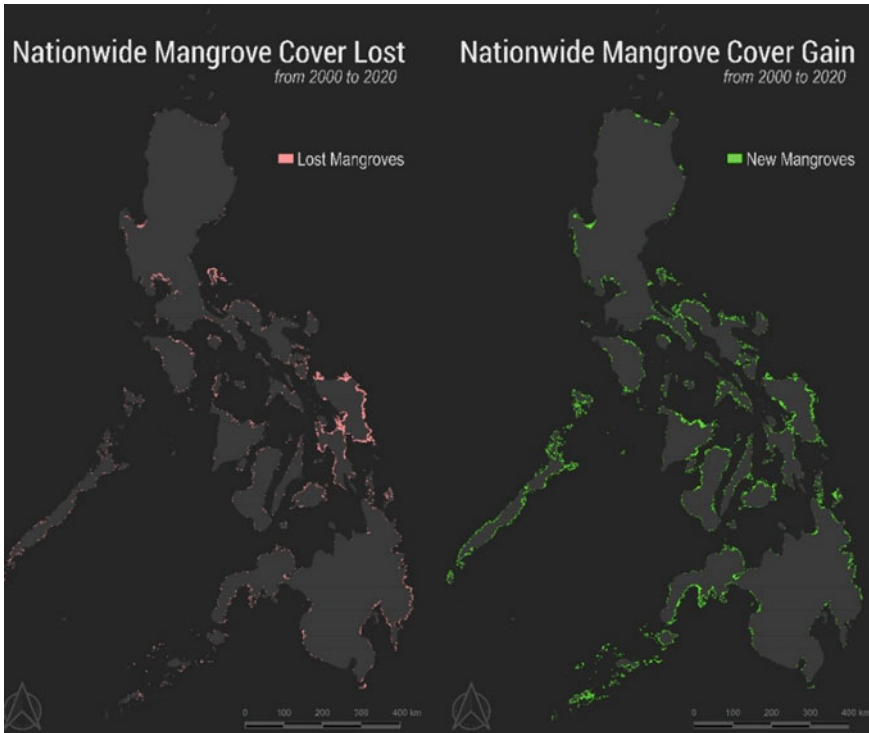
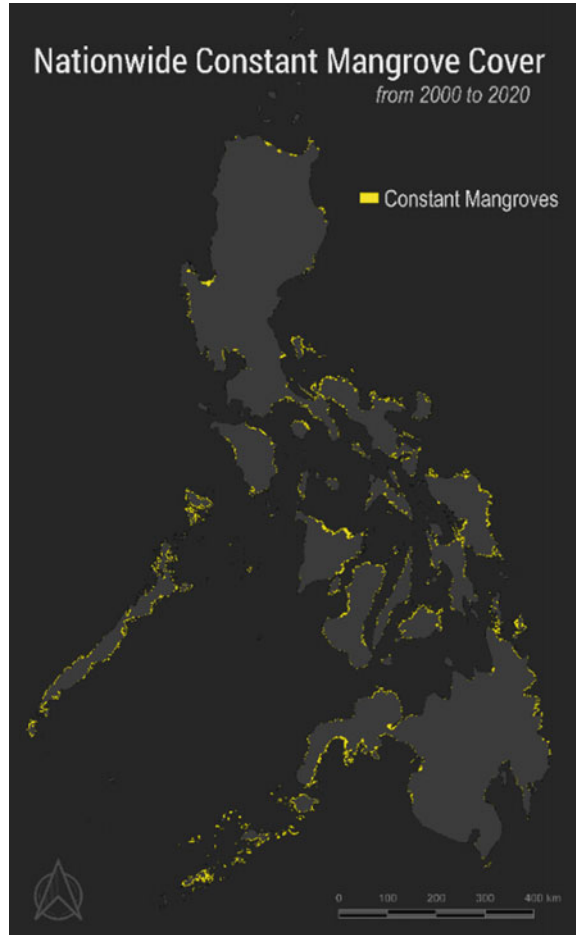


Fig. 12.6 Nationwide mangrove cover lost (left) and cover gained from year 2000 to 2020

needed. In terms of decadal trend of mangrove extent in the Philippines from other references, the result of the current study is comparable with the mangrove trend from Global Mangrove Watch (Bunting et al. 2018) from 1996 to 2016. GMW also reported a general decreasing trend, although the reported mangrove loss is relatively lower (9,000 Ha) than the lost calculated in this study for 2000 to 2020 (29,000 Ha). Meanwhile, in the Long and Giri study, a decreasing trend was also observed between the earliest (1990) and latest (2010) estimates, with a loss of 28,172 Ha (Long and Giri 2011). The differences in the observation periods between among these studies may have affected the variations in the lost mangrove estimates, in addition to the differences in the satellite data and applied methodologies.

Fig. 12.7 Nationwide retained mangrove cover from year 2000 to 2020. The distribution of retained mangroves was observed throughout the country, even to areas frequently visited by typhoons. This may signify natural resiliency and regrowth in mangrove forests, or by human-assisted forest recovery



Impacts of Climate Related Variables

Effect of Rainfall on Mangrove Extent

Rainfall in the Philippines is influenced by the northeast (NE) monsoon and southwest (SW) monsoon and the climate regions, which are based on monsoonal rainy seasons (Coronas 1920). Matsumoto et al. (2020) used the TRMM 3B42 rainfall 1998–2013 to analyze climatological seasonal changes of rainfall in the Philippines. Results from this study show that rainfall in the Philippines is influenced both by the NE and SW monsoon. During the SW monsoon season, the west coast of the Philippines receives relatively higher rainfall compared with the east coast of the country. This is

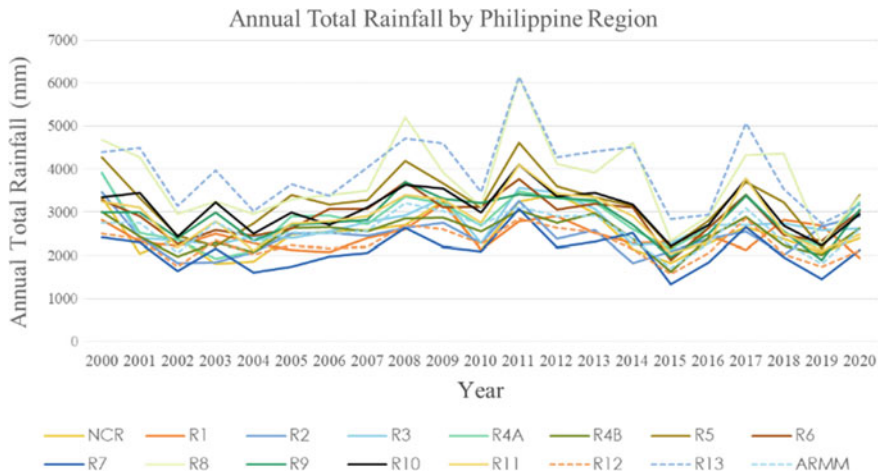


Fig. 12.8 Annual total rainfall (mm) in each Philippine region from 2000 to 2020. Most of the regions have similar annual trends as influenced by climatic patterns such as El Niño and La Niña

attributable to tropical cyclone (TC) activities that can also enhance SWM rainfall. In addition to monsoon, rainfall distribution in the Philippines is also influenced by the location of the mountain systems. The mean annual rainfall of the Philippines varies from 965 to 4,064 mm annually (PAGASA).

Based on CHIRPS data, the annual total rainfall was calculated as shown in Fig. 12.8.

Relatively higher amounts of annual total rainfall were recorded in years 2000, 2008, 2011, and 2017. High amounts of rainfall were received by regions 13, 8, 4B, 10, and 11. The rainfall statistics among regions follows similar trend, especially during the La Niña years such as 2007–2008 and 2017–2018 wherein a significant increase in rainfall was observed across all regions.

The decadal rainfall difference shows varying results among regions (Table 12.2). Almost all regions have lower precipitation in the later year (2020) than in year 2000. Highest decadal rainfall differences were calculated in regions 8, 13, 5, and 3, ranging from –883 mm to –1,320 mm. Only one region (region 9) recorded an increase in annual rainfall amount (+63 mm) after two decades.

In this study, mangrove extent data was regressed with rainfall metrics including decadal total rainfall, mean annual rainfall, and mean annual rainfall increment (Fig. 12.9).

Decadal total rainfall, mean annual increment, and mean annual rainfall show positive correlation with mangrove loss. Between the rainfall metrics, the mean annual rainfall increment gave the highest correlation ($r = 0.68$). This implies that the higher the decline in mean annual rainfall (higher variability), the higher the loss in mangrove area (Fig. 12.9). Changes in rainfall patterns have significant impacts

Table 12.2 Decadal rainfall difference from 2000 to 2020 calculated using CHIRPS data. Negative difference implies decreased amount of rainfall in 2020 compared to value two decades earlier

Region	Decadal rainfall difference (mm)
R1	-873.34
R2	-557.03
R3	-1292.61
R4A	-676.96
R4B	-379.64
R5	-883.32
R6	-250.43
R7	-284.7
R8	-1320.57
R9	63.83
R10	-390.64
R11	-753.46
R12	-388.22
R13	-1232.83
NCR	-951.33
ARMM	-158.11

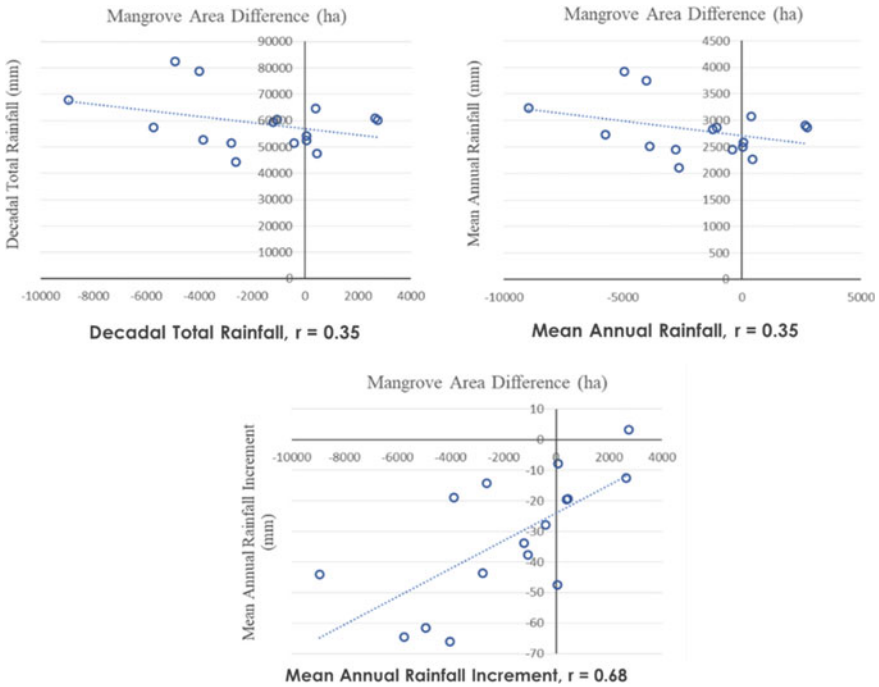


Fig. 12.9 Correlation results between mangrove extent and rainfall variable metrics. The mean annual rainfall increment generated higher correlation with the mangrove extent loss data

on mangrove growth, extent, and spatial distribution and have been suggested as a mechanism for the landward growth of mangroves (Gilman et al. 2008; Eslami-Andargoli et al. 2009). Decrease in rainfall also resulted to mangrove loss in other countries as reported by previous studies (Ghosh et al. 2017; Eslami-Andargoli et al. 2009).

Reduced precipitation over an area decreases water input to groundwater and lesser freshwater surface water input to mangroves, thereby increasing salinity. The increase in soil salinity induces pore water salinity, resulting in increased tissue salt levels in mangrove trees, which then decreases water availability and consequently reduces productivity and low seedling survival (Gilman et al. 2008). Decreased precipitation and rise in sea levels could result in salinity and inundation stresses (Salmo and Juanico 2015) and changing competition between species of mangrove (Ellison 2000). Mangrove population located in highly saline and frequently inundated sites may eventually collapse despite indicators of being healthy during the early stages of its development (Salmo and Juanico 2015). Meanwhile, the increase in precipitation is known to have a significant positive relationship with mangrove areas due to the landward expansion of mangrove (Eslami-Andargoli et al. 2009).

Mangrove productivity is increased as a result of decreased pore water salinity and sulfate concentration due to increased precipitation (Gilman et al. 2008). However, this increase in growth rate as a response to increase in precipitation could be species-specific (Krauss et al. 2014). Therefore, species that can adapt or tolerate such condition have competitive advantage over non-adaptive species.

Further analysis was done by identifying first the major climate type in each region, and clustering together the regions with similar climate type (Fig. 12.10). This analysis greatly improved the correlation results as the climate types were mainly characterized based on the occurrence and frequency of precipitation. The mangrove extent data was also re-grouped based on the regions belonging to the same climate type.

By clustering first the regions by climate type, correlation results for all rainfall metrics greatly increased (Table 12.3). The mean annual rainfall increment has an R-value of 0.99 compared to the 0.68 R-value when rainfall metrics were aggregated directly by region. The correlation coefficients for mean annual and decadal total rainfall also increased. Among the Philippine climate types, higher mean annual increments and higher mangrove losses were observed in areas classified under Types I and II. These areas have longer and more pronounced wet season.

In the aggregated precipitation metrics by climate type, it was observed that the mean annual rainfall increment is significantly lower in areas under Type III, possibly due to the occurrence of less pronounced wet season.

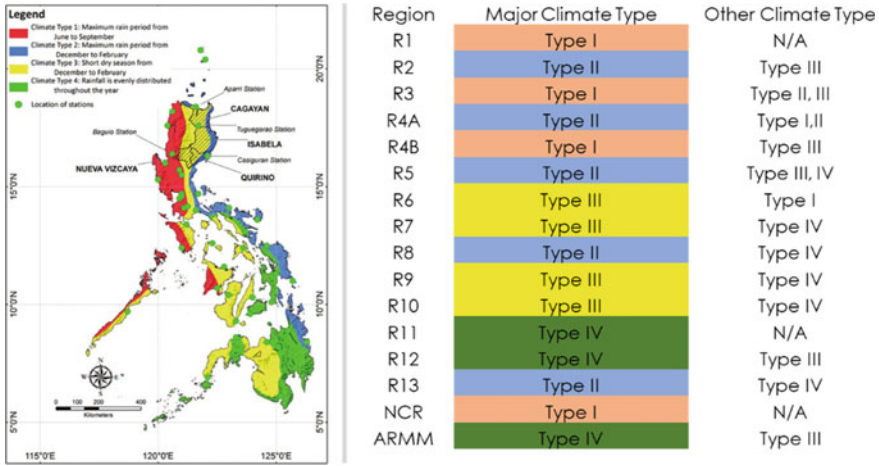


Fig. 12.10 The Philippine climate type map (left, Basconcillo et al. 2016) and the dominant climate type for each of the administrative regions. Most of the regions have other climate types aside from the major climate, but identification of the dominant type was necessary to group regions per climate category

Effect of Typhoon Frequency on Mangrove Extent

The typhoon tracks data obtained from NOAA International Best Track Archive are shown in Fig. 12.11 and Table 12.4. These tracks were recorded from year 1999–2019.

There are relatively fewer typhoons that devastated the regions in Mindanao island or those regions in the southern part of the country (Fig. 12.11). Most of the typhoon tracks are recorded in Luzon and in the eastern portion of Philippines such as Eastern Visayas and Bicol Region.

Based on the mangrove loss and typhoon data statistics, areas that were least devastated by typhoons (fewer than 10 typhoons, gray-shaded rows in Table 12.4) have recorded increased vegetation cover such as in Northern Mindanao (Region 10), and Zamboanga Peninsula (Region 9). Regions with greater frequency of typhoons have declined mangrove areas, including regions 3, 4B, 5, and 8.

Results of linear regression (Fig. 12.12) show moderate positive correlation between typhoon count and mangrove loss ($r = 0.43$). Typhoon frequency was positively correlated with mangrove loss mainly due to the destructive impacts of typhoons such as lower mangrove productivity, canopy defoliation, uprooting of trees, and rapid decrease in soil elevation (Cahoon et al. 2003; Paling et al. 2008; Ward et al. 2016). Similar correlation results between typhoon frequency and mangrove structure were reported by other studies (Adame et al. 2013; Simard et al. 2019; Lin et al. 2020; Rovai et al. 2016).

Table 12.3 Correlation between mangrove extent and rainfall metrics aggregated by major climate type. Since climate types were defined based on the amount, timing, and distribution of rainfall, correlating mangrove loss and rainfall with this unit generally improved the correlation results

Climate Type	Climate Type Description	Mangrove Area Difference (ha)	Mean Annual Rainfall (mm/year)	Mean Annual Rainfall Increment (mm)	Decadal Total Precipitation (mm)
Type I	Has two pronounced seasons: dry from November to April and wet throughout the rest of the year.	-3082.75	2550.52	-43.71	53560.94
Type II	Characterized by the absence of a dry season but with a very pronounced maximum rain period from November to January	-3898.60	3236.81	-46.71	67972.98
Type III	Seasons are not very pronounced but are relatively dry from November to April and wet during the rest of the year.	793.50	2737.73	-10.77	57492.28
Type IV	Characterized by a more or less even distribution of rainfall	-186.67	2574.39	-21.66	54062.16
Mangrove Extent Difference vs Rainfall Variable		Multiple r	0.51	0.99	0.51

Typhoon-induced damages in mangrove forests are well documented in the Philippines, such as studies assessing the impact of Typhoon Haiyan in 2013 (Long et al. 2016; Buitre et al. 2019) and Typhoon Chan-hom in 2009 (Salmo et al. 2013). Multiple studies were conducted to monitor the changes in typhoon frequency and intensity in the country. DOST-PAGASA (2018) reported a slightly decreasing number of typhoons while a slightly increasing number of intense typhoons. Global reports also cited low confidence on the multi-decadal to centennial trends in the frequency of typhoons, while increase in the occurrence of stronger typhoons was certain in the past four decades (IPCC 2021).

Effect of Sea Surface Temperature on Mangrove Extent

The SST data for years 2003 and 2020 for selected Philippine regions are shown in Fig. 12.13. Higher SST values was recorded in 2020 for all regions, especially during the drier months of May to August. Closer SST values between the two dataset were recorded within the months of January and February.



Fig. 12.11 The Philippine typhoon track from year 2009 to 2019 (Source NOAA IBTrACS). The occurrence of typhoons (blue lines) was heavily concentrated in Luzon and Visayas islands

Among the SST metrics, the average annual maximum SST generated the highest correlation with mangrove loss ($r = 0.39$) (Fig. 12.15). Lower correlation values were obtained with the mean SST difference ($r = 0.22$) and lowest with the average annual minimum SST ($r = 0.11$) (Fig. 12.14). The higher the annual maximum SST, the higher the loss in mangrove area. Each mangrove species grows within a specific SST threshold and exceeding this limit may result to inhibition of physiological

Table 12.4 Number of Typhoons and the corresponding mangrove area difference per region

REGION CODE	REGION	Mangrove Area Difference (ha)	Number of Typhoons (1999-2019)
R1	Ilocos Region	-2784	36
R2	Cagayan Valley	-409	51
R3	Central Luzon	-5738	26
R4A	CALABARZON	-1211	19
R4B	MIMAROPA	-3857	36
R5	Bicol Region	-8940	28
R6	Western Visayas	2657	25
R7	Central Visayas	-2628	20
R8	Eastern Visayas	-4007	33
R9	Zamboanga Peninsula	2748	4
R10	Northern Mindanao	397	9
R11	Davao Region	-1061	8
R12	SOCCSKSARGEN	439	3
R13	Caraga	-4926	19
NCR	Metropolitan Manila	46	7
ARMM	ARMM	62	2

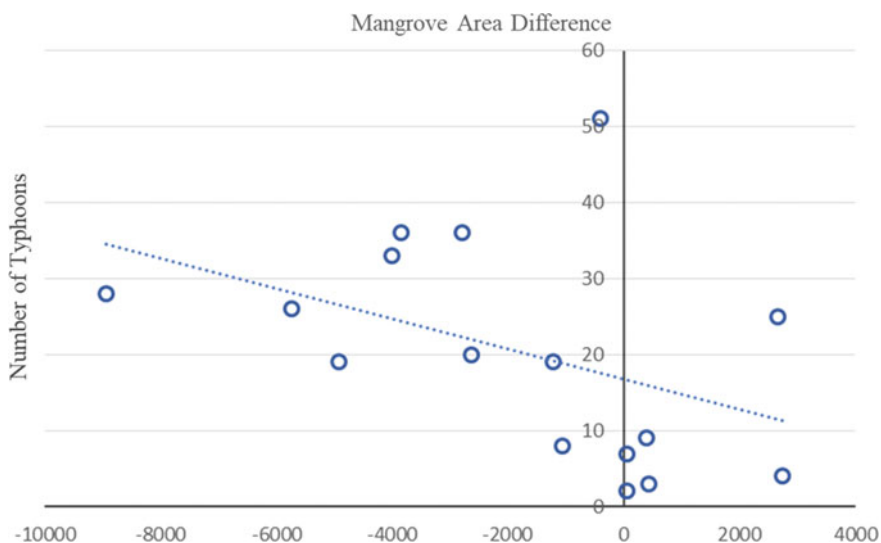


Fig. 12.12 Correlation between mangrove area difference and typhoon track count per region from 1999–2019. A positive correlation was observed between these variables due to the direct and non-direct impacts of extreme weather events to any vegetated land cover



Fig. 12.13 Comparison between the Average Monthly SST (°C) in 2003 and 2020 in selected Philippine regions. Consistently higher monthly SST values were recorded in 2020 than 2003

functions of the plant, including the growth of propagules. High sea temperatures (as reflected with max SST) induced mangrove loss as mangrove survival and seed germination is limited within specific SST levels (Duke et al. 1998; Woodroffe and Grindrod 1991).

SST is a predominant variable that can regulate seedling growth of mangrove propagules during the dispersal stage. The success or failure of the formation of propagules in new lands depends essentially on SST after being transported by sea water. Very low values of SST may also hinder mangrove growth as it may suppress and lessen the growth of mangrove propagules (Ximenes et al. 2016).

Effect of Sea Surface Height on Mangrove Extent

The differences in SSH between the observation period were calculated and shown in Table 12.5. The greatest increase is plus 0.18 recorded in region 11 (Davao Region), while the greatest decline (0.17) was recorded in region 9 (Zamboanga Peninsula) with minus 0.17 in the SSH data. Most of the regions within the Luzon island have increased SSH values.

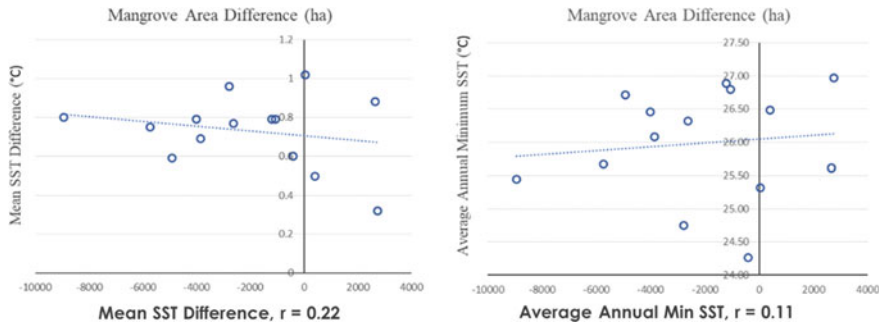


Fig. 12.14 Correlation results between mangrove extent and Mean SST and Average Annual Minimum SST. The SST metrics gave the lowest correlation to mangrove loss among the climate-related factors considered in this study

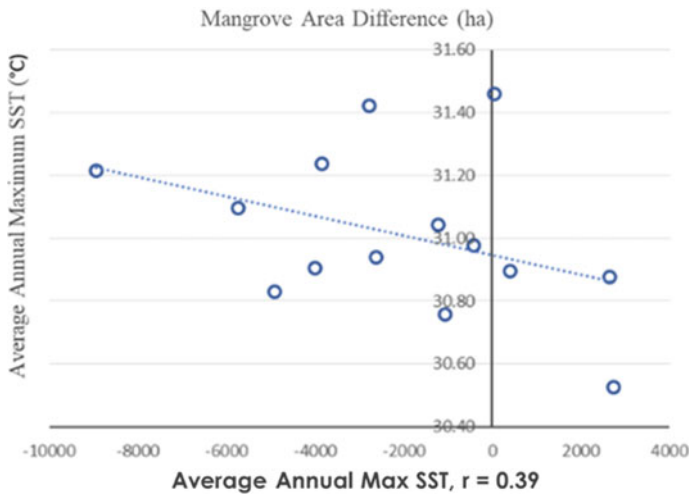


Fig. 12.15 Correlation results between mangrove extent and Average Annual Maximum SST

Sea level rise, which is regionally variable, is likely to have varied yet minimal impacts on mangroves locally (Ward et al. 2016). In this study, mangrove extent data was regressed with the difference in SSH within the administrative regions. Results showed a very low positive correlation ($r = 0.16$) between mangrove area difference and sea surface height difference (Fig. 12.16). Previous studies also reported very minimal impacts of SSH (Ward et al. 2016; Friess et al. 2012).

It was reported by previous studies that mangroves can adapt to sea-level rise if it occurs slowly enough. With minimal changes in sea surface level relative to mangrove surface, and other factors such as salinity, period, and depth of inundation will also remain constant, the mangrove margins and the inhabiting mangrove community will remain the same (Gilman 2006). Change in elevation within mangrove forests

Table 12.5 SSH difference and the corresponding mangrove area difference per region

Region	Mangrove extent difference (ha)	Sea surface height difference (m)
R1	-2784	-0.17
R2	-409	0.02
R3	-5738	0.00
R4A	-1211	0.10
R4B	-3857	-0.05
R5	-8940	-0.07
R6	2657	-0.02
R7	-2628	0.03
R8	-4007	-0.10
R9	2748	-0.17
R10	397	-0.10
R11	-4926	0.18
R13	-4926	-0.04
NCR	48	0.01

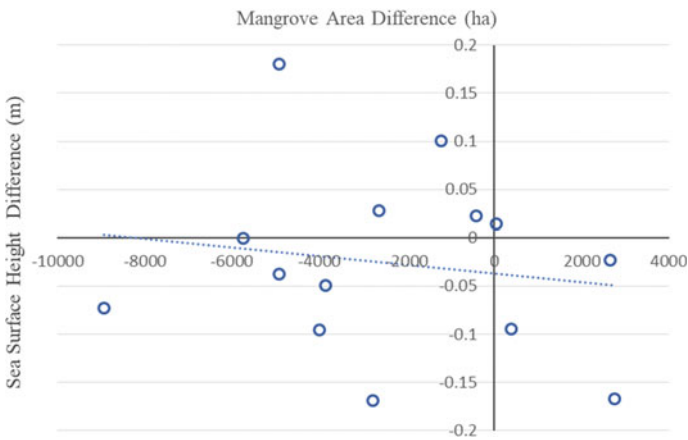


Fig. 12.16 Correlation results between mangrove extent and SSH decadal difference (m)

normally occurs at very slow rates which leads to directional changes over long time periods (Krauss et al. 2014). The two-decade observation in this study may not be long enough to capture these changes in sea surface heights. In comparison, the global mean sea level increase between 1901 and 2018 is 20 m, with an average increase rate of 3.7 mm yr⁻¹ between 2006 and 2018 (IPCC 2021).

To persist, mangrove ecosystems must adapt to rising sea level by growing vertically through vertical accretion or deposition on the soil surface. Previous studies show that during periods of slower historical rise, mangrove soils were able to adapt

to sea-level rise by building vertically through sediment deposition and peat formation, and mangrove forests expanded in many locations (Krauss et al. 2014; McKee et al. 2007; Willard and Bernhardt 2011).

Effect of Historical Air-Sea Climate Exposure on Mangrove Extent

The Philippines is vulnerable to the ill-effects of climate change due to its extreme exposure to increasing ocean temperature, extreme rainfall events and sea level rise. Such extreme conditions can also have a negative effect on the coastal habitats such as mangroves, seagrasses and corals (David et al. 2015; Lovelock et al. 2015). The study of David et al. (2015) provided the different levels of exposure to these variables as a significant input to national vulnerability assessments.

The mangrove extent data was regressed with the level of relative exposure per climatic variable which include increasing ocean temperature, extreme heating events, extreme precipitation, rainfall changes, and sea level rise. The level of exposure varies among the regions and among the climatic variables (Table 12.6).

Table 12.6 Relative exposure level and the corresponding mangrove area difference per region. A value of 1 implies lower level of exposure while 5 implies higher level of exposure to each of the climatic variables below

Region	Mangrove area difference	Level of relative exposure per climatic variable (Highest: 5)				
		Increasing ocean temperature	Extreme heating events	Extreme precipitation	Rainfall changes	Sea level rise
R1	-2784	3	5	5	5	5
R2	-409	3	5	2	3	4
R3	-5738	3	5	2	3	4
R4A	-1211	2	4	1	5	5
R4B	-3857	2	4	1	5	5
R5	-8940	3	4	4	4	4
R6	2657	3	3	1	3	5
R7	-2628	3	3	1	3	5
R8	-4007	5	4	4	3	4
R9	2748	3	3	1	3	5
R10	397	5	4	4	3	4
R11	-1061	5	4	3	1	5
R12	439	3	3	1	3	5
R13	-4926	5	4	4	3	4
NCR	48	2	4	1	5	5
ARMM	62	3	3	1	3	5

Table 12.7 Selected climatic variables and the correlation results with mangrove loss. Regions with higher relative exposures recorded higher mangrove area loss, especially those exposed to extreme heating events, extreme rainfall, and occurrence of sea level rise

Historical climatic variable	Multiple R
Increasing ocean temperature	0.1
Extreme heating events	0.47
Extreme rainfall	0.51
Rainfall changes	0.19
Sea level rise	0.54

Multiple R	Main Climate-Related Variables									Exposure Ranking with Climatic Variables				
	Decadal Total Rainfall	Mean Annual Rainfall	Mean Annual Rainfall Increment/Region	Mean Annual Rainfall Increment/Climatic Type	Total Typhoon	Mean SST Difference	Average Annual Minimum SST	Average Annual Max SST	Sea Level Height Difference	Increasing Ocean Temperature	Extreme Heating Events	Extreme Precipitation	Precipitation Changes	Sea Level Rise
	0.35	0.35	0.68	0.99	0.43	0.22	0.11	0.39	0.16	0.1	0.47	0.51	0.19	0.54

Fig. 12.17 Correlation of climate-related variables with mangrove extent loss (2020–2000)

Losses in mangrove covers were observed in regions with high exposure to extreme precipitation ($r = 0.51$), extreme heating ($r = 0.47$), and sea level rise ($r = 0.54$) (Table 12.7).

The summary of correlation between the climate-related variable and mangrove loss is shown in Fig. 12.17. Numbers highlighted in blue are variables with relatively higher correlation results.

Impacts of Human-Induced Variables

Mangrove Forest Conversion to Built-Up

A total of 200 Ha of mangroves were converted to built-up from years 2000 to 2020 (Table 12.8). This is only 0.1% of the total decadal mangrove loss (29,208 Ha). The highest area converted to built-up was recorded in region 7 (62 Ha).

Mangrove Forest Conversion to Fishponds

A total of 1,409 Ha of mangroves were converted to fishponds from years 2000 to 2020 (Table 12.9). This is less than 1% of the total decadal mangrove loss (29,208 Ha). Highest percentage of converted area to fishponds was recorded in regions 10 and 12 (8.5%). It must be noted that in the Philippines, mangrove conversion to fishponds largely took place in 1951–1988 (Friess et al. 2019; Primavera 1995) in which the rate of fishpond expansion after this period is lower based on NAMRIA data. Less

Table 12.8 Mangrove area converted to built-up cover in each Philippine region

REGION CODE	REGION	NAMRIA LAND COVER DATA	
		Mangrove Area (ha) Converted to Built-up	% Converted Area
R1	Ilocos Region	<i>No mangroves detected in 2006 NAMRIA LC</i>	
R2	Cagayan Valley	6.26	0.59
R3	Central Luzon	<i>No intersection</i>	
R4A	CALABARZON	0.49	0.01
R4B	MIMAROPA	36.69	0.14
R5	Bicol Region	6.69	0.04
R6	Western Visayas	8.58	0.10
R7	Central Visayas	62.58	0.67
R8	Eastern Visayas	23.24	0.09
R9	Zamboanga Peninsula	4.39	0.04
R10	Northern Mindanao	6.49	0.26
R11	Davao Region	0.15	0.01
R12	SOCCSKSARGEN	0.53	0.13
R13	Caraga	41.87	0.40
NCR	Metropolitan Manila	<i>No mangroves detected in 2006 NAMRIA LC</i>	
ARMM	ARMM	2.00	0.03
TOTAL		199.96	0.14

mangrove cover lost from fishpond conversion were also reported by NAMRIA between 2006 and 2015, with an area that is only 7% of the total converted areas prior to 2006. Declining rates of loss may be attributed to already reduced cover, improved data quality, and to national and international conservation policies (Primavera 1995, 2000). Further improvement and longer analysis of aquaculture maps can provide more coherent results.

The highest built-up area conversion from mangroves was recorded in Central Visayas (63 Ha) and lowest in Davao region (0.15 Ha). Meanwhile, the highest fishpond area conversion from mangroves was recorded in Zamboanga Peninsula (330 Ha) and lowest in Davao region (2.8 Ha). Limitations in the resolution of satellite images used have resulted to some regions with no reported mangroves like Metro Manila and Ilocos Region, specifically on the 2006 land cover data.

Conclusions

To understand the impacts of human-induced and climatic variables on mangroves, relationship between these factors must be identified both in the temporal and spatial scales. In this study, decadal mangrove extent was the metric used in describing the potential impact of selected human and climate-related variables on the mangrove

Table 12.9 Mangrove area converted to fishponds cover in each Philippine region

REGION CODE	REGION	NAMRIA LAND COVER DATA	
		Mangrove Area (ha) Converted to Fishponds	% Converted Area
R1	Ilocos Region	<i>No mangroves detected in 2006 NAMRIA LC</i>	
R2	Cagayan Valley	4.05	0.38
R3	Central Luzon	48.46	0.73
R4A	CALABARZON	73.23	0.84
R4B	MIMAROPA	158.33	0.59
R5	Bicol Region	72.51	0.45
R6	Western Visayas	86.64	1.02
R7	Central Visayas	151.14	1.61
R8	Eastern Visayas	151.42	0.62
R9	Zamboanga Peninsula	330.47	3.21
R10	Northern Mindanao	212.83	8.52
R11	Davao Region	2.83	0.10
R12	SOCCSKSARGEN	34.75	8.47
R13	Caraga	82.52	0.78
NCR	Metropolitan Manila	<i>No mangroves detected in 2006 NAMRIA LC</i>	
ARMM	ARMM	<i>No intersection</i>	
TOTAL		1409.19	1.01

forests in the Philippines. Multi-decadal mangrove extent maps were generated with the use of Landsat-derived Mangrove Vegetation Index layers. Although there are already existing historical estimates of mangrove area, a standardized index-based mapping workflow is needed in reliably detecting actual changes on the ground. An overall trend of decreasing mangrove extent was observed in the Philippines from 2000 to 2020 with the annual losses surpassing the annual gains. The extent of vegetation gain and loss varies per region, and this was associated with the variables considered in this study.

Variations in the climate-related variables have all impacted the extent of mangrove communities. Linear regression results highlight significant relationships between major climate variables and the decadal extent of mangrove forests. Among these variables, the mean annual rainfall increment, annual max SST, and number of typhoons have the greatest correlation and thus considered as the main drivers of decadal mangrove loss in the country. This observation agrees with previous studies on the correlation of mangrove forest statistics with rainfall variability, maximum SST, and typhoon frequency. In addition, historical exposures to sea level rise and extreme heating and precipitation events were positively correlated with the decline in mangrove areas. The level of correlation of climatic variables with mangrove loss also varies per region and per climate type.

There is a minimal percentage of mangroves that were converted to built-up and fishpond areas during the period considered. Around 1% of the total mangroves were converted to fishponds. Less mangroves loss from fishpond conversion were also reported by NAMRIA between 2006 and 2015. Most of the mangrove-to-fishpond conversion in the country took place a long time before the period used in this study (1950s to 1970s). After the said period, land use conversion still took place but is now controlled and limited due to the strict regulations and continuous monitoring of concerned Philippine agencies.

This study highlighted the vulnerability of Philippine mangrove forests to natural and climate-related factors. Results of this study provide valuable information to better manage and protect mangrove forests especially those located in areas that are frequently visited by typhoons, with declining annual rainfall, and areas exposed to maximum temperature during the dry months. Identifying the main threat to mangrove per region will also help in selecting effective region-specific interventions.

Recommendations

- The results of this study can be utilized in drawing site-specific intervention to the local threats on mangroves. For instance, stronger naturally growing frontline
- mangrove species must be selected whenever there are replanting activities within regions frequently visited by typhoons. Species that are more tolerant to increasing sea temperatures must be selected within regions having high SSTs. Further, the methodologies used in this study can be applied to provincial level for a more spatially detailed analysis.
- Improvement and continuation of effective mangrove management and monitoring strategies and programs, including regulation of mangrove to fishpond conversion.
- Capacity-building of local government officials on the use of MVI and other remote sensing data for rapid and accurate monitoring of mangrove forest.
- Dissemination of information to the target community on the importance and vulnerability of mangroves, and the steps to protect and conserve these resources.
- This study assessed the impacts of climatic variable using selected metrics only. There are other potential metrics that can be included in further studies such as land subsidence and typhoon intensity. For human-induced metrics, historical data on aquaculture conversion is needed to capture more extended observations.

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