Hindawi
Advances in Meteorology
Volume 2022, Article ID 9693303, 10 pages
https://doi.org/10.1155/2022/9693303

Research Article

Variation of Leaf Area Index (LAI) under Changing Climate: Kadolkele Mangrove Forest, Sri Lanka

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Received 14 March 2022; Accepted 27 September 2022; Published 10 October 2022

Academic Editor: Gabriele Buttafuoco

Mangroves are an essential plant community in coastal ecosystems. While the importance of mangrove ecosystems is well acknowledged, climate change is expected to have a considerable negative impact on them, especially in terms of temperature, precipitation, sea level rise (SLR), ocean currents, and increasing storminess. Sri Lanka ranks near the bottom of the list of countries researching this problem, even though the scientific community's interest in examining the variation in mangrove health in response to climate change has gained significant attention. Consequently, this study illustrates how the leaf area index, a measure of mangrove health, fluctuates in response to varying precipitation, particularly during droughts in Sri Lanka's Kadolkele mangrove forest. The measurements of the normalized difference vegetation index (NDVI) were used to produce the leaf area index (LAI), which was then combined with the standard precipitation index (SPI) to estimate the health of the mangroves. The climate scenario, RCP8.5, was used to forecast future SPI (2021–2100), and LAI was modeled under the observed (1991–2019) and expected (2021–2100) drought events. The study reveals that the forecasted drought intensities modeled using the RCP8.5 scenario have no significant variations on LAI, even though some severe and extreme drought conditions exist. Nevertheless, the health of the mangrove ecosystem is predicted to deteriorate under drought conditions and rebound when drought intensity decreases. The extreme drought state (-2.05) was identified in 2064; therefore, LAI has showcased its lowest (0.04). LAI and SPI are projected to gradually increase from 2064 to 2100, while high fluctuations are observed from 2021 to 2064. Limited availability of LAI values with required details (measured date, time, and sample locations) and cloud-free Landsat images have affected the study results. This research presents a comprehensive understanding of Kadolkele mangrove forest under future droughts; thus, alarming relevant authorities to develop management plans to safeguard these critical ecosystems.

1. Introduction and Background

Mangrove forests are critical coastal resources that contribute significantly to the socio-economic growth of a country. They are salt-tolerant woody plants with a diverse taxonomic range (around 80 species) and can be found in the intertidal zone of coastal areas [1]. The mangrove ecosystem is a natural habitat for various birds, fish, shellfish, and etc. At the same time, it provides a range of goods and services such as wood and marine products, preventing storm damage, controlling floods and coastal erosion, and recreation [2–5]. Although mangroves are an essential part of the environment, mangrove forests have already lost more than half of their original land due to deforestation and other human activities. A globally rare yet highly threatened coastal forest ecosystem, mangroves cover approximately 137,760 km^2–152,360 km^2 of the world's surface [6]. A total of 73 mangrove species and hybrids are dispersed across 123 countries and territories around the globe [7]. In addition, changing climates play a vital role in this degradation. Trends appear to be continuing despite the importance of these unique coastal habitats for meeting human needs and may disappear in about 50 years [2, 8].

Therefore, it is critical to pinpoint the factors that impact the mangrove ecosystem. Many factors cause the degradation of the mangrove ecosystem. However, climate change's

projected consequences, such as increases in global temperature and carbon dioxide concentration, as well as changes in ocean circulation and rainfall/drought patterns, are significant [9–11]. According to IPCC (2013), there will be a notable shift in precipitation patterns accompanied by substantial regional variation. Temperature variations, which influence evaporation and transpiration rates, will make variable precipitation even more problematic.

Changing precipitation patterns are projected to affect mangrove forests' distribution, extent, and growth rates, particularly in areas where mangroves are close to the limits of their tolerances [13]. Extreme fluctuations in precipitation, for instance, may affect the seasonal average salinity in particular mangrove systems, but the effect would vary across the fringe, estuarine, and interior mangroves. Decreased precipitation and increased evaporation enhance soil salinity, influencing seedling production, growth rates, mangrove loss, and conversion to hypersaline mudflats (apicum) in the upper tidal zone over decades [14, 15]. Reference [16]. During increasing precipitation, the landward migration of mangroves into the salt marsh zone, which occurs near the mangrove's landward limit, was also linked to an increase in mangrove area [16]. In mangroves where there is very little change in soil moisture, Krauss et al. [17] suggest that reactions to the rise in precipitation may be species-specific in mangroves (i.e., Micronesia). Sonneratia alba exhibits high growth rates in response to increased precipitation, but Brugieira gymnorhiza shows no reaction. In addition to lowering pore water salinity and sulfate levels, increasing precipitation may stimulate mangrove formation [18]. Additionally, it is projected that an increase in precipitation will lead to a rise in riverine flow. This will improve allochthonous sediment imports, mangrove surface elevation, and resistance to SLR in estuary mangroves [19].

Temporal variation of the health of forest cover is usually assessed by ecological indicators such as total leaf area, respiration, canopy cover, biomass, and photosynthesis [20]. The leaf area index (LAI) has strongly related to the exchanges of water, energy, and CO_2 between forests and the environment. Therefore, LAI is a crucial biophysical variable for measuring forest health [2, 21–24]. LAI is described as half of the total area of green space divided by the area of the horizontal ground [25]. LAI is a component of the system's canopy. The dynamics of canopy growth in conjunction with the drop in canopy cover indicate that vegetation is under stress. Because of that, LAI can be used as an indicator of mangrove health levels [26]. Based on the above-mentioned data, the LAI serves as a regulator of microcanopy features such as water absorption in the canopy and radiation barriers. The geographical distribution of LAI must be mapped in order to collect data on mangrove health. The temporal variation of LAI can be extracted from historical satellite images and therefore, remote sensing techniques can effectively be used to quantify the health and the structural changes of the forests [27, 28].

The structure of mangrove forests and their productivity have been analyzed by many researchers [16, 29, 30]. In addition, the impact of ongoing climate change is frequently assessed on mangrove forests. Alongi [9, 31] has reviewed state-of-the-art knowledge of climate change in mangrove forests due to its importance. Osland et al. [30] identified and quantified the climate-mangrove linkages in eastern North America, eastern Australia, New Zealand, East Asia, eastern South America, and southeast Africa. Murdiyarso et al. [32]; Ward et al. [33]; and Alongi [34] are few other examples of research work carried out on the analysis of the impact of climate change on mangrove forests in various regions of the world.

However, some research can be found in the literature on the impact of future climates on mangrove ecosystems [35, 36]. Mafi-Gholami et al. [36] analyzed three regions, namely Khamir, Tiab, and Jask in Iran and found that LAI changed in 1998. This followed the same patterns of mean annual rainfall and drought occurrences; therefore, the relationship between LAI and climate is validated. They also expected to observe decreases in LAI and SPI by 2030, reaching their lowest values between 2040 and 2070 in their study region. Therefore, the impact of projected droughts on the mangrove ecosystem is essential to understand.

Many disciplines discussed the importance of the mangrove ecosystem in Sri Lankan coastal belts [37–41]. Jayakody et al. [42] performed a study to analyze the vegetation structure and potential gross primary productivity of mangroves at the Kadolkele mangrove forest. Although some research has been conducted on the Kadolkelle mangrove forest [42, 43], to the authors' knowledge, the impact of future climate changes on mangrove forests is never analyzed in the context of Sri Lanka. The relationships between LAI and droughts based on climatic scenarios such as Representative Concentration Pathways (RCP4.5,. . .,RCP8.5) were hardly found in the literature for Sri Lanka. However, Sri Lanka has over 6000 ha of mangrove cover (5009 ha in dry and arid zones, 644 ha in intermediate zone, and 430 ha in wet zone) [44]. Nevertheless, as stated above, none has attempted to determine how drought affects a mangrove's health. Hence, the objective of this study is to identify, for the first time, how the leaf area index (LAI: as an indicator used to forecast health) varies during droughts in one of the mangrove forests in Sri Lanka; the Kadolkele mangrove forest.

2. Materials and Methods

2.1. Study Area. The Kadolkele mangrove forest, located at (7°11′49.82″N, 79°50′32.29″E) Negombo estuary in western Sri Lanka, was selected as the study area (refer to Figure 1). Kadolkele mangrove forest is an intact forest covering an area of 10 hectares and is a significant place for mangrove studies [45, 46]. The geographical region of the Kadolkele mangrove forest receives a cumulative annual mean rainfall of 2400 mm and an average temperature of 24°C–30°C throughout the year [47].

The diversity of mangrove species in the Kadolkele mangrove forest is extensive, with 29 mangrove species observed, 18 of which are classified as true mangroves [48]. They have further identified 33 additional mangrove-associated vegetation types. The three mangrove families, Rhizophoraceae, Avicenniaceae, and Combretaceae, are the most frequently found mangrove families in the Kadolkele

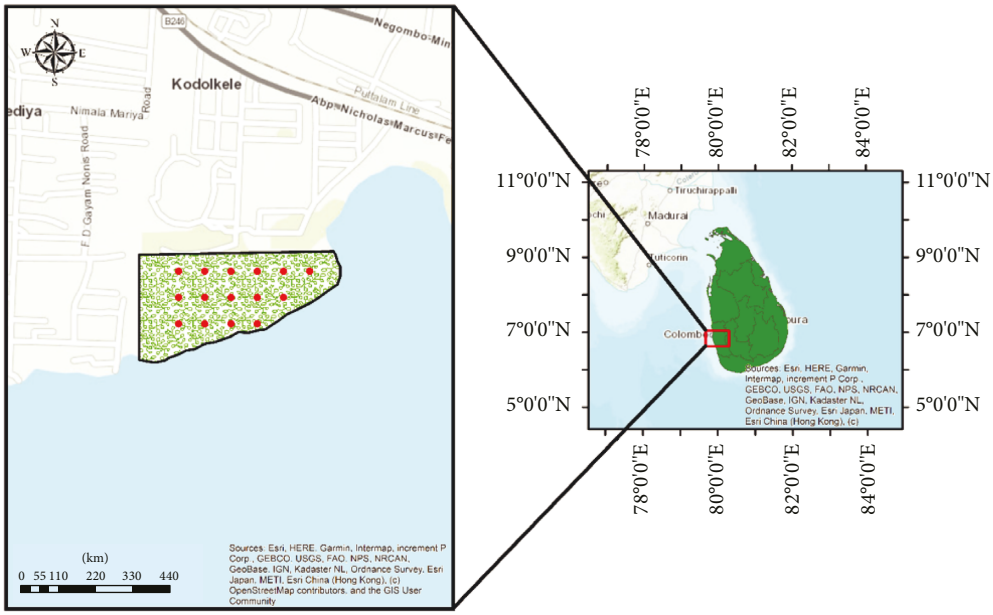

Figure 1: The geographic location of the study area with the sample plots (Red circles).

forest. *Rhizophora apiculata* and *Rhizophora mucronata* are the most abundant Rhizophoraceae species. *Avicennia marina* is the major Avicenniaceae species in this mangrove forest, whereas Lumnitzera racemose is the most abundant Combretaceae species. Therefore, the Kadolkele mangrove forest provides an essential balance to the Negombo estuary ecology [49].

2.2. Analyzed Data

2.2.1. Leaf Area Index (LAI). The ratio of the areas (m^2) of single-sided green leaves to the surface of the ground is termed the leaf area index. It estimates the amount of leaf area in an environment and is a critical element of photosynthesis, respiration, and precipitation absorption [50–53]. The international climate change research community has highlighted LAI as a crucial climatic variable since it is fundamental to the world's vegetation [54]. Additional information about LAI can be identified in Fang et al. [55].

$$\text{LAI} = \frac{\text{Leaf area}}{\text{Ground area}}. \tag{1}$$

LAI is hard to assess due to its spatial (horizontal and vertical) and temporal instability. Different optical, allometric, litter collecting, and remote sensing procedures may be used to calculate LAI [56].

The rapid expansion of the canopy and the loss of canopy cover suggest that vegetation is under stress. As a result, LAI may be used to assess the health of mangroves [26]. Moreover, LAI controls microcanopy properties, including water absorption and the creation of a radiation barrier. LAI distribution must be mapped to acquire data on the health of mangroves. For assessing and mapping spatial components of LAI, remote sensing provides benefits over direct LAI measurement. It also serves as a monitoring tool [57].

2.2.2. Normalized Difference Vegetation Index (NDVI). In remote sensing, the NDVI is a well-known and often used indicator [58]. The TOA reflectance ratio of a red band (ρ_{RED} around 0.66 μm) to a near-infrared (NIR) band is used to compute NDVI (ρ_{NIR} around 0.86 μm). The NDVI of a densely forested region is more likely to be favorable than that of water or urban areas, which have NDVI values near zero or negative.

Generally, NDVI is given by Braun and Herold [59] as follows:

$$\text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}}. \tag{2}$$

According to a study conducted by Green et al. [60] using NDVI as a proxy, the normalized difference vegetation index (NDVI) is a vegetation index often used to calculate LAI. The NDVI can assess a region's vegetation's health and level of greenness.

2.2.3. Standard Precipitation Index (SPI). The standard precipitation index is a modern drought index that primarily focuses on precipitation occurrence (SPI) [61]. It is a probability-based index that may be applied at any time. Atmospheric conditions have a short-term impact on specific activities, such as dryland agriculture. Various processes occur over months, such as the pace at which shallow wells, little ponds, and minor rivers become drier or wetter. It takes a few years for significant reservoirs, aquifers, and extensive natural bodies of water to rise and fall, while other processes take longer.

Tom McKee, Nolan Doesken, and John Kleist of the Colorado Climate Center established the SPI in 1993. Using SPI, precipitation may be assigned a single numerical value for comparison across locations with markedly different climates. The SPI's standardization enables it to assess the present drought's rarity.

Table 1: Drought intensities according to SPI values [63].

SPI values	Drought category
0 to −0.99	Mild drought
−1.00 to −1.49	Moderate drought
−1.5 to −1.99	Severe drought
≤−2.0	Extreme drought

When wet conditions are present in one or more periods, the standardized precipitation index (SPI) indicates that dry conditions may also be present. Consequently, a unique value for the SPI is determined for several periods.

SPI can be calculated using the following formula:

$$\mathrm{SPI} = \frac{x_i - \overline{x}}{\sigma}, \tag{3}$$

where x_i, $\overline{x}$, and σ are precipitation at i^{th} rain gauge, long-term mean precipitation, and standard deviation, respectively. Different temporal scales of the SPI indicate different drought impacts on water resources. SPI values of 1 to 3 months (short time scale) indicate changes in soil moisture that have the potential to have a significant impact on agriculture, whereas SPI values of 6 to 12 months or more (long time scale) reflect long-term changes in precipitation, surface, and underground waters, and water resources across an entire region, with significant consequences for ecosystem function and water resource management in human settlements [62]. McKee et al. [63] defined the SPI values for different drought conditions, as seen in Table 1.

2.2.4. Meteorological Data. The Sri Lankan Meteorological Department is the source for rainfall figures for the period commencing from 1991 to 2019. Researchers could better comprehend the relationship between LAI and SPI as a result of this evaluation of the standard precipitation index (SPI).

In the RCP scenario, it was anticipated that the inquiry findings would continue to be reliable until 2100. There are four distinct RCPs, and each has its own unique set of assumptions about population growth and economic development, in addition to energy consumption and the sources of that energy. The RCPs (representative concentration pathways), the four scenarios represented by RCP2.6, RCP4.5, RCP6, and RCP8.5, provide an estimated range of radiative forcing levels in 2100 in comparison to preindustrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively). The emission assumptions for various gases serve as the foundation for these scenarios. Additional data on RCPs can be found in van Vuuren et al [64].

When concentrations reach their steady state in 2250, the RCP8.5 radiative forcing levels are projected to increase to 12 W/m^2 from 8.5 W/m^2 by the end of this century. This RCP may be implemented even if no further measures are made to reduce carbon emissions. Schwalm et al. [65] stated that the RCP 8.5 scenario has long been recognized as the "worst-case scenario" for climate change in 2050. It was determined that RCP 8.5 would be used since it is the method that is utilized the most often for assessing scientific problems to make decisions.

2.3. Methodology

2.3.1. Development of a Relationship between LAI and NDVI. The primary objective of this research is to determine the impacts of climate change on mangrove health. To accomplish this, an integrated modeling technique was adopted, integrating previously gathered information from mangrove studies (LAI) with Landsat satellite imagery and climate data. Historical LAI values for 1991–2019 were estimated using the literature found LAIs and normalized difference vegetation index (NDVI) data.

Although field sampling is the best way to determine the LAI, due to resource constraints, the LAI data were gathered from Jayakody et al. [42]. They have measured LAIs during both the wet and dry seasons; however, due to the nature of our study, we only collected LAI data for the dry season, March and April being the two driest months in the Kadolkele mangrove forest.

Jayakody et al. [42] did not provide the specific sample sites, i.e., the coordinates. This was a significant concern. As a result, the authors assumed these coordinates. As illustrated in Figure 1, the whole research area was divided into 63 m × 63 m grids for this study. Every one of the 15 preset sample locations has a value for the LAI that was chosen randomly.

Landsat satellite imagery (paths/raw # 141/055) was used to retrieve the NDVI values for these gridded locations. Landsat images were obtained from the United States Geological Survey (USGS) Earth Explorer (https://earthexplorer.usgs.gov/) between 1991 and 2019 using Landsat 4/5 TM and Landsat 8 OLI, respectively. The extracted image tile (141/055) is shown in Figure 2. All these Landsat images are in the raster format and 30 m resolution. The images were obtained during drier seasons to avoid undesired inaccuracies. A higher percentage of cloud cover can usually be seen in the wet season. This can result in an increased reflection in a dense forest cover due to the high reflectance in the red and near-infrared bands [66, 67].

The least-squares regression analysis was performed to develop a relationship between NDVI and LAI for 2007. Then, the regression model was applied for the 29 years (1991–2019) of NDVI values extracted from Landsat images to predict corresponding LAI values. The most precise image (cloud-free) possible between March and April was considered without considering a specific date for the LAI field survey. The errors could be minimized in the event of the same date for both measurements. However, the study was under two months of evaluation. Therefore, the LAIs were assumed as an average value for those two months from the literature.

2.3.2. Development of a Relationship between LAI and SPI. After developing a set of LAI values from 1991 to 2019 using the relationship between LAI and NDVI, the relationship between LAI and SPI was established to predict the response

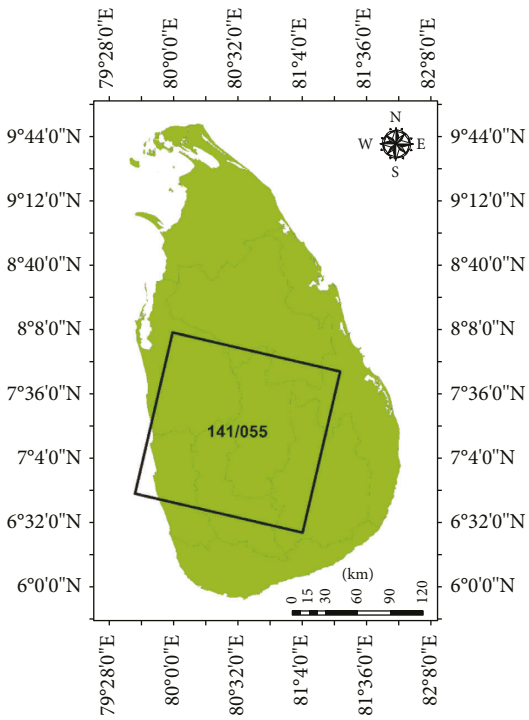

Figure 2: Landsat tile arrangement of 141/055.

of mangrove health to climate change. The model was developed using the least-squares regression analysis.

The 12-month average SPI for 1991–2019 was calculated using the observed rainfall at Katunayake meteorological station (7°10′11.9994″ N, 79°52′47.9994″ E). It is the closest meteorological station to the Kadolkele mangrove forest (5.141 km away). The standardized precipitation-evapotranspiration index package developed by Beguería et al. [68] was used in the R software platform to calculate the SPIs.

2.3.3. Projection of SPI Values with RCP8.5 Climate Change Scenario. The forecasted rainfall data for 92 years from 1991 to 2005 (for historical data) and 2022 to 2100 (for future data) were extracted using four regional climate models, namely MPI-ESM-CCAM, ACCESS-CCAM, REMO2009, and CNRM-CCAM for Katunayake meteorological station coordinates. These raw rainfall data were bias-corrected using the linear scaling (L.S.) method [69]. Previous studies have shown that the L.S. method performs better in coarse temporal scale analysis than more complicated methods, such as quantile mapping, delta change, and power transformation [70, 71]. The historical rainfall data from RCP8.5 and ground observations were matched to process the bias correction as per Equations (4) and (5). Equations (4) and (5) have indicated the mathematical formulation for bias correction.

$$\mathrm{RF}^{*}_{\mathrm{his}}(d) = \mathrm{RF}_{\mathrm{his}}(d) \times \frac{\mu_m(\mathrm{RF}_{\mathrm{obs}}(d))}{\mu_m(\mathrm{RF}_{\mathrm{his}}(d))}, \quad (4)$$

$$\mathrm{RF}^{*}_{\mathrm{sim}}(d) = \mathrm{RF}_{\mathrm{sim}}(d) \times \frac{\mu_m(\mathrm{RF}_{\mathrm{obs}}(d))}{\mu_m(\mathrm{RF}_{\mathrm{his}}(d))}, \quad (5)$$

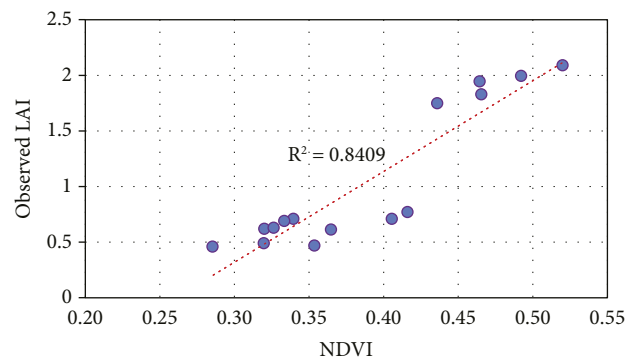

Figure 3: Relationship between observed LAI to NDVI.

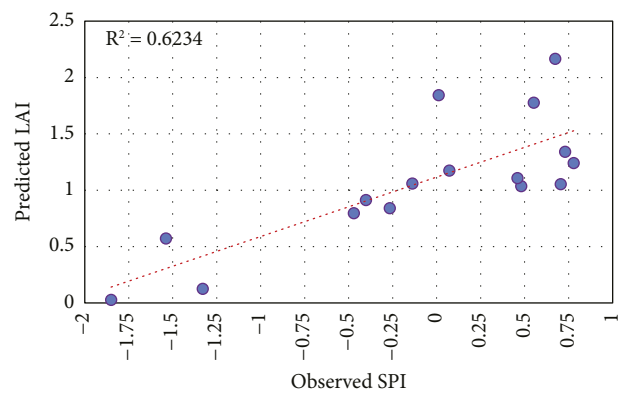

Figure 4: Relationship between predicted LAI to observed SPI.

Where "*" indicating bias-corrected data, "his" stands for raw RCM hindcast, "obs" stands for observed data, "sim" stands for raw RCM-corrected data, and finally "RF" and "d" stand for precipitation and daily, respectively. "μ_m" is the long-term monthly mean of the precipitation data.

3. Results and Discussion

3.1. Relationship between LAI and NDVI. The relationship developed for 2007 using observed LAI values and extracted NDVI values is shown in Figure 3. The coefficient of determination (R^2) was 0.84, and the P value was 0.001 ($P < 0.001$), indicating that the relationship is acceptable and statistically significant for future analysis. Furthermore, using the linear regression model, a set of LAI values was compiled to examine the relationship between LAI and SPI for the 29 years from 1991 to 2019.

3.2. Relationship between LAI and SPI. Then, the predicted LAI values for 29 years (1991–2019) were compared to the SPI values. The relationship was statistically found significant ($P < 0.001$), with a $R^2 = 0.62$. Figure 4 presents the relationship. The coefficient of determination showcases a somewhat reduced value; however, it still presents a relationship between predicted LAI and observed SPI.

However, SPI values do not show a noticeable trend from 1991 to 2019. They fluctuate from positives to negatives and so on. Figure 5 presents the temporal variation of SPIs for the

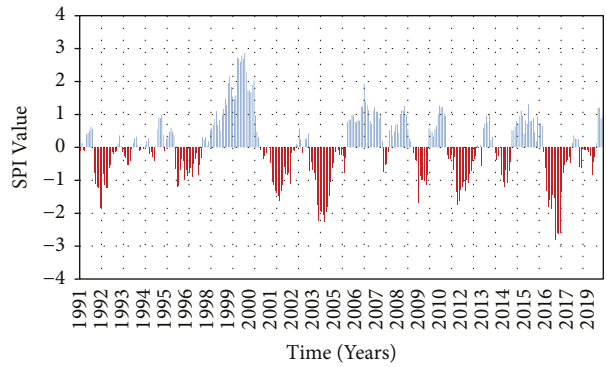

Figure 5: Temporal variation of SPI values for 29 years (1991–2019).

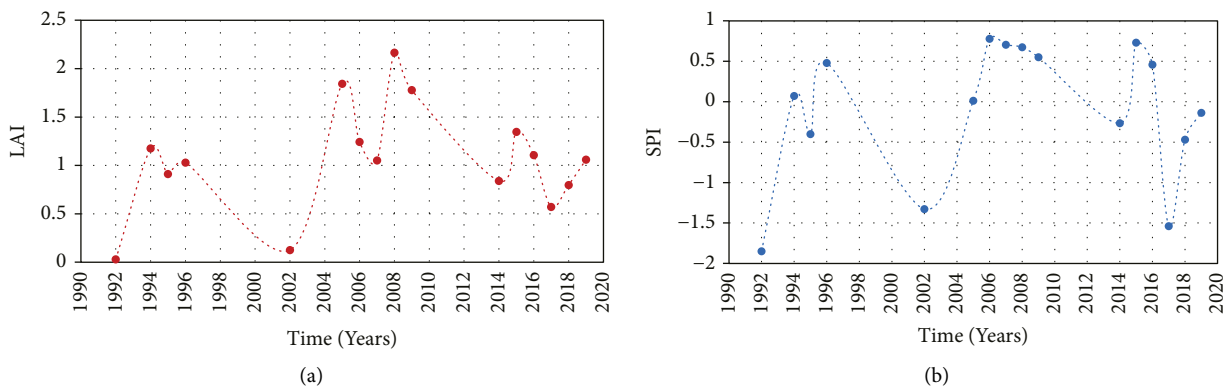

Figure 6: LAI was derived from the NDVI and SPI values over 29 years (1991–2019). (a) For LAI. (b) For SPI.

29 years of historical data. These were calculated using the monthly mean rainfall data for Katunayake meteorological station.

However, both the SPI and LAI values followed a similar trend (Refer to Figure 6), demonstrating that the SPI is strongly related to the LAI and climbed abruptly in response to increased rainfall. In contrast, LAI values decreased in response to decreasing rainfall.

Severe droughts can be seen in 1992 (SPI = −1.85) and 2017 (SPI = −1.54), respectively, with LAI values of 0.03 and 0.57, while a moderate drought occurred in 2002 (SPI = −1.33) with an LAI of 0.13. Therefore, the relationship between LAI and SPI can be visualized. In addition, the SPI plot's ups and downs clearly illustrate the climate's behavior, and a future drought is possible.

3.3. Mangrove Health Projection Based on the Relationship between LAI and SPI. The forecasted climate scenario RCP8.5 was used to predict the monthly rainfall (in mm), then the annual SPI values were derived for the period of 78 years (2022–2100). Three-time periods were used to showcase the results, including near future (2022–2040), mid-future (2041–2070), and far-future (2071–2100). The relationship between SPI and LAI was then applied to produce the LAI values, and Figures 7(a)–7(c) present the project SPIs and LAIs for the three-time periods.

As was expected, LAIs and SPIs follow similar patterns. No severe droughts were found in the near future (2022–2040), even though it is expected to have drought conditions from Figure 6 (via visual expectations). In fact, the year 2032 presents the highest LAIs, a critical environmental condition for the Kadolkele mangrove forest (LAI = 2.63). However, Figure 7(b) illustrates a severe drought in the year 2064. It has an SPI of −2.05 while the LAI is at 0.04, which is the lowest for the mangrove forest.

Nevertheless, this can be considered a warning to the authorities to get ready with the ground conditions. Far-future does not showcase severe droughts under RCP8.5 climate conditions. However, some milder droughts can be expected.

It is clear that declining LAI values within a study area are generally associated with declining forest health. Hence, the LAI values in the Kadolkele study ranged between 0.03 and 2.16 from 1991 to 2019 and 0.04 and 2.63 from 2022 to 2100. The forecast has mixed findings. LAI was reduced to 0.04, which is an extreme situation for the health of the mangrove forest. Therefore, preserving mangrove forests must be considered an essential coastal task.

LAI has been successfully associated with investigations of mangrove health in several studies [36, 72–74], and it has been extensively used as a biophysical parameter in ecological research [75]. Alongi et al. [76] reported that healthy *Avicennia* Marina forests in Western Australia had a mean

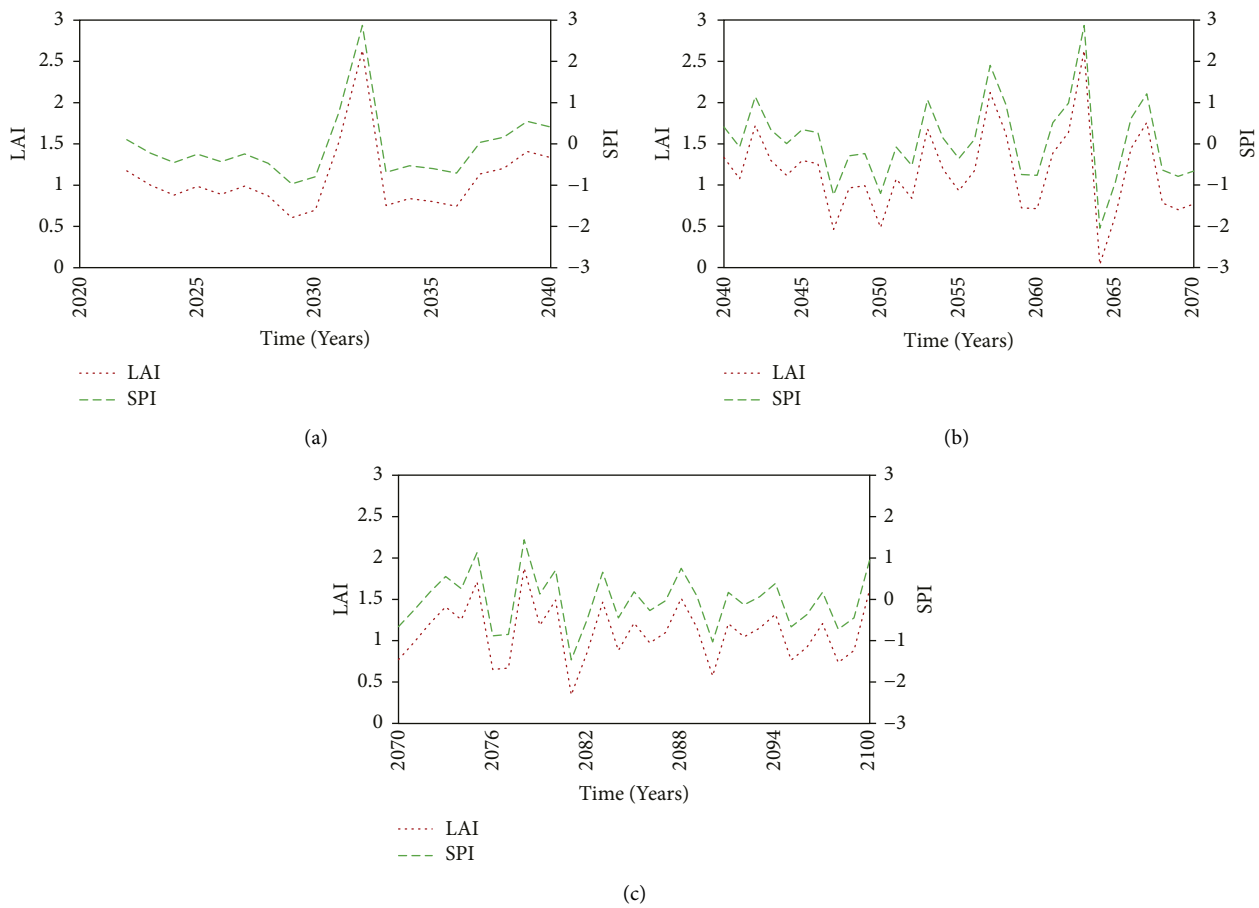

Figure 7: Projected SPI and LAI under RCP8.5 climate scenario. (a) For 2022–2040. (b) For 2041–2070. (c) For 2071–2100.

LAI of 4, whereas degraded and low-production forests had a mean LAI of 2.7. Similarly, Lovelock and Ellison, [77] reported that the *Avicennia* Marina forest had a mean LAI of 1.4, but decreased to 1 as the forest degraded in New Zealand. However, absolute values of mangrove LAIs cannot be compared across study regions due to their strong dependence on a variety of environmental factors such as air temperature, evapotranspiration, rainfall, nutrients in the soil, sea level, pollution, geomorphological characteristics, structure, and composition of mangrove [72, 78, 79].

Therefore, the results of this research suggested some important warnings to the authorities and stakeholders involved in coastal-related activities. The results can be considered as some preliminary points to investigate the situation further and then develop a proper conservation plan.

4. Conclusion

This study investigates the impacts of climate change on the anticipated health and LAI values of mangrove forests from 2022 to 2100, based on the link between the present SPI and observed LAI. Additionally, this study highlights a linear relationship between the LAI and the SPI. The RCP8.5 climate scenario predicts that the Kadolkele Mangrove Forest in 2064 will experience drought conditions, which might have a catastrophic impact on the health condition of mangroves—except for 2064, prior and future years had a mixed record of severe and minor droughts. It is anticipated that the health of the mangrove ecosystem will deteriorate due to the dry conditions but will improve after the severity of the drought has lessened (1991–2019).

The effect of the environment's site-specific traits, in addition to long-term trends in rainfall and drought, would put pressure and stress on the evaluated results. It is probable that environmental factors such as rising sea levels and temperatures, increased usage of fossil fuels, and the entry of pollutants harmful to mangroves may cause damage to those mangroves in the future. Consequently, future research should consider these traits when developing mangrove ecosystem management strategies.

Due to a lack of other relevant data, the Kadolkele mangrove forest will serve as the only focus of this research. Since this is an island nation with a significant amount of mangrove forest, the research should be broadened to include the entire country. The outcomes of such a study have the potential to be incorporated into Sri Lanka's national policy for the preservation of coastal ecosystems and mangrove forests.

Data Availability

The climatic data used in this research study are available upon request for research purposes.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The study was carried out under the SLIIT research grant FGSR/RG/FE/2021/06 and authors would like to acknowledge the support that they had from Sri Lanka Institute of Information Technology (SLIIT), Sri Lanka.

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