Development of a Forest Resilience Index Combining Multispectral and Microwave Vegetation Indices

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Abstract—*Sri Lanka is one of the few surviving countries in the world with an extensive natural forest cover, however, most of the existing forest has been impacted by changing environmental conditions and escalating disturbances. To preserve our forest environment, investigating its temporal resilience is important. Forest Resilience is the capacity of forests to recover from disturbances in which they experience undesired shifts from their original state to available alternative stable. This research study mainly focused to analyse the resilience of forests Wilpattu National Park and Kanneliya Rain Forest with a time series of the Landsat 8/9 and Sentinel 1 satellite imagery during the period of the year 2017 to 2022 by generating Forest Resilience Index (FRI). In this study, Landsat 8/9 and Sentinel 1 satellite images were used to create the NDVI, LAI and RVI layers. Then time series analysis was conducted with values of NDVI, LAI and RVI. The final outcomes were Forest Resilience Indices that were generated with NDVI and RVI. The FRI for Wilpattu National Park is 0.7827NDVI + 0.2173RVI and for Kanneliya Rain Forest is 0.7853NDVI + 0.2147RVI. The validation was conducted with generated FRI for the Upper Wilpattu area and it was succeeded. This analysis helped to analyse the temporal variability indicating the resilient dynamics of the Sri Lankan forests.*

***Keywords* — Forest Resilience Index, LAI, NDVI, RVI, Time Series Analysis**

I. INTRODUCTION

Forests are the most significant naturally occurring renewable resources, playing a crucial role in human existence and the environment (Prăvălie, 2018). Forest ecosystems are becoming threatened by changing environmental drivers and intensifying disturbances mostly caused by changes in climate and land use (McDowell et al., 2020). Therefore, the concept of forest resilience has emerged as a crucial framework to identify how forests respond to disturbances or threats.

A. Forests and Forests in Sri Lanka

Forests are complex and diverse ecological systems dominated by trees. They are the most important renewable natural resources that provide numerous benefits to humans and the environment including climate regulation, carbon sequestration, biodiversity conservation, water resource management and soil protection (Arce, 2019). In Sri Lanka, forests cover approximately 29% of the land area and play a critical role in sustaining the country's economy, environment, and cultural heritage.

B. Forest Disruptions

Forest disruptions refer to any events or factors that cause significant changes to the composition, structure, and functioning of a forest ecosystem. The major forest ecosystems are becoming threatened by changing environmental factors and increasing disturbances mostly caused by changes in climate and land use (Prăvălie, 2018).

C. Forest Resilience

Resilience is the ability of an ecosystem (in this case, a forest type) to recover from a disturbance while retaining its core taxonomic composition, ecological functions, structures and process rates (Holling, 1973). The need for more research on forest resilience has emerged as a key concern in ecological environment monitoring (Messier et al., 2019).

D. Remote Sensing for Forest Resilience

Remote sensing can play a crucial role in assessing forest resilience. It can provide valuable information on various forest variables, such as vegetation structure, biomass, and health that can be used to monitor the changes and assess the resilience of forests in the face of climate change and other disturbances. By integrating remote sensing data with ground-based observations, forest managers can develop more accurate and efficient monitoring strategies to identify vulnerable areas and implement appropriate management actions to enhance forest (Lechner et al., 2020). Additionally, remote sensing can help in detecting early signs of stress or damage in forests, allowing for timely interventions to minimize the impact of disturbances and promote forest recovery.

II. METHODOLOGY AND EXPERIMENTAL DESIGN

The methodology includes describing the methods required to obtain the results. And also, it explains the study area and the methods of data collecting.

A. Study Area

The study was focused in Wilpattu National Park (8.4564° N, 80.0476° E) and Kanneliya Rain Forest (6.2579° N, 80.3600° E) which are major forests in Sri Lanka.

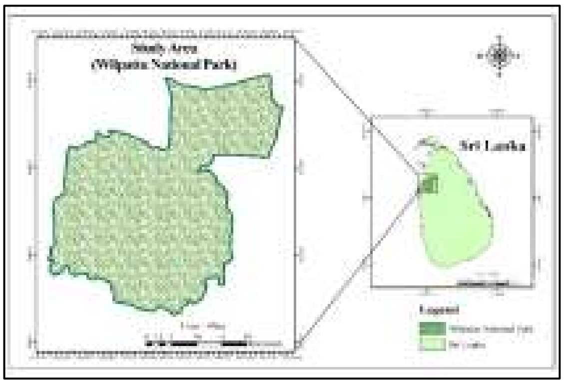

Figure 1: Study Area 01 - Wilpattu National Park

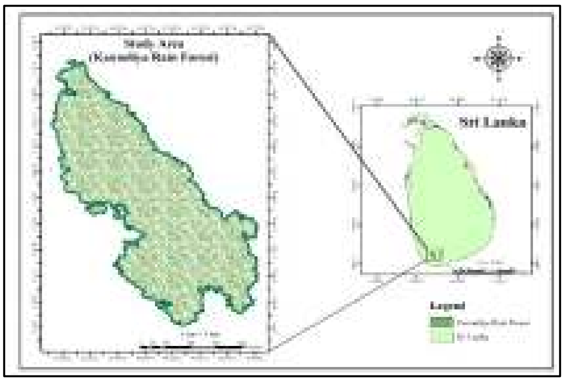

Figure 2: Study Area 02 - Kanneliya Rain Forest

B. Flow chart of methodology

The flow chart represents the key steps to obtain the results of this study.

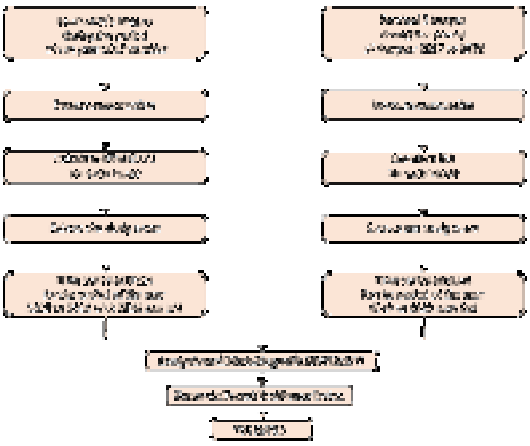

Figure 3: Flow Chart of Methodology

C. Data Collection

Table 1: Data and Data Sources

Data	Source
Landsat 8/9 satellite images from 2017 to 2022	USGS Earth Explorer
Sentinel 1 satellite images from 2017 to 2022	NASA Earthdata
Shape files of the study areas	Open Street Map

D. Data Organization

After collecting all the satellites images, image pre-processing was done. Then Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) layers for each Landsat 8/9 satellite images were created. Using Sentinel 1 satellite images, Radar Vegetation Index (RVI) layers were created. Ten Regions of Interest (ROIs) were created for each study area and NDVI, LAI and RVI values were extracted for each ROIs. Then Time Series Analysis was conducted for NDVI, LAI and RVI with time period of 2017 to 2022.

$$\text{NDVI} = \frac{NIR-RED}{NIR+RED} \quad \text{(Pettorelli, 2013)}$$

$$\text{LAI} = \frac{-\ln\left(\frac{0.69-SAVI}{0.59}\right)}{0.91} \quad \text{(Enoh et al., 2022)}$$

$$\text{SAVI} = \frac{(NIR-RED)1.5}{(NIR+RED+0.5)} \quad \text{(Enoh et al., 2022)}$$

$$C_2 = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} \langle |S_{VV}|^2 \rangle & \langle S_{VV} S_{VH}^* \rangle \\ \langle S_{VH} S_{VV}^* \rangle & \langle |S_{VH}|^2 \rangle \end{bmatrix} \quad \text{(Barakat, 1977)}$$

$$m = \sqrt{1 - \frac{4|C_2|}{(Tr(C_2)^2}} \quad \text{(Barakat, 1977)}$$

$$\text{DpRVI} = 1 - m\beta; \; 0 \leq \text{DpRVI} \leq 1 \quad \text{(Barakat, 1977)}$$

E. Statistical Analysis

The time series analysis plot (ROI) that has the minimum standard deviation was selected for the calculation of the Stability Index. Then Stability Index was calculated by using the ratio between the standard deviation of NDVI into standard deviation of RVI. Since Stability Index was high, the ROI was selected as the Persistent Vegetation Plot. By combining these two persistent vegetation plots, the scatter plot of NDVI Vs RVI was plotted. Then a linear regression line was fitted into this scatter plot. With a visual inspection, the outliers were removed. After removing the outliers, then again the scatter plot of NDVI Vs RVI was plotted. A linear regression line was fitted to this scatter plot and the gradient of graph was assigned to the weight of NDVI. Next the weight of RVI was assigned as the one minus gradient of graph. Once finding out the weights of each parameters of NDVI and RVI, the Forest Resilience Index for each study area was generated with inverse weighted mean method. Next Forest Resilience Indices were mapped throughout the study time period for both study areas.

F. Validation

The validation was conducted for an area that selected form Upper Wilpattu area. The area was fulfilled with trees in 2017 and was deforested in 2018. The FRI index that generated for Wilpattu National Park was applied and validation was done.

III. RESULTS AND DISCUSSION

After implementing the methodology of the study for both study areas, the results have been obtained.

A. Created Layers of NDVI, LAI and RVI

The NDVI, LAI and RVI layers were created for time period 2017 to 2022. The created Layers are shown as follow. Extracted values are tabulated here.

Table 2: Extracted Values of NDVI,LAI and RVI in Wilpattu National Park

Year	NDVI	LAI	RVI
2017	-0.0928 - 0.5152	-0.1704 - 4.5070	0 - 0.8544
2018	-0.1195 - 0.4568	-0.1707 - 5.2780	0 - 0.9118
2019	-0.0704 - 0.4515	-0.1699 - 4.2087	0 - 0.8806
2020	-0.2112 - 0.5687	-0.1719 - 4.0693	0 - 0.8975
2021	-0.1332 - 0.3810	-0.1699 - 1.7638	0 - 0.8388
2022	-0.2438 - 0.6613	-0.1721 - 3.5494	0 - 0.9434

Table 3: Extracted Values of NDVI, LAI and RVI in Kanneliya Rain Forest

Year	NDVI	LAI	RVI
2017	0 - 0.5471	-0.1290 - 10.9851	0 - 0.7538
2018	0 - 0.5803	-0.1648 - 9.1824	0 - 0.8005
2019	0 - 0.4949	0 - 8.9039	0 - 0.8004
2020	0 - 0.5419	0 - 9.7270	0 - 0.7898
2021	0 - 0.5519	-0.0783 - 10.1653	0 - 0.7341
2022	0 - 0.6240	-0.0363 - 10.3254	0 - 0.7734

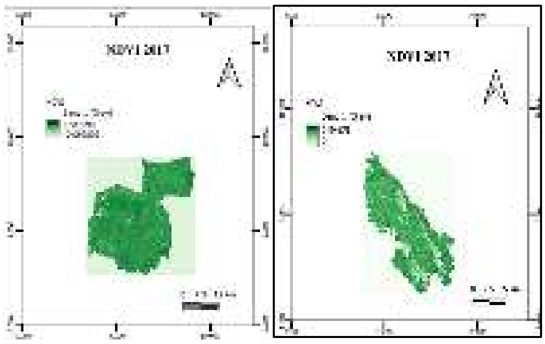
Figure 4: NDVI Layers

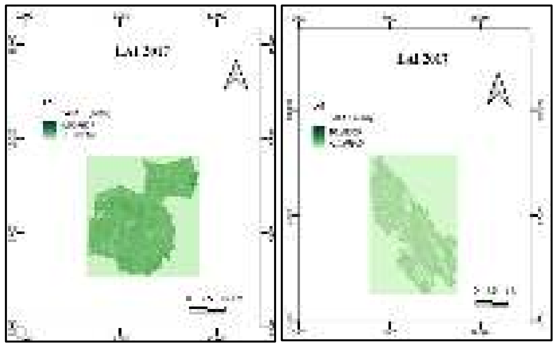
Figure 5: LAI Layers

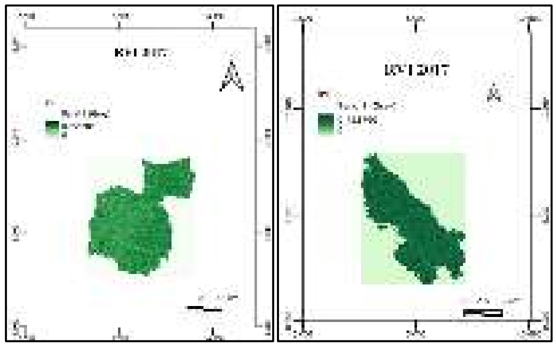
Figure 6: RVI Layers

B. Analysis of Standard Deviations of NDVI, LAI and RVI values

The standard deviation values of NDVI, LAI and RVI values were analyzed with time series analysis and the ROI which has the minimum standard deviation was selected for calculate the stability index to find Persistent Vegetation Plot.

Table 4: Standard Deviation Values of each Region of Interests

	Wilpattu National Park		Kanneliya Rain Forest	
ROIs	SD of NDVI	SD of RVI	SD of NDVI	SD of RVI
01	0.0171	0.0685	0.0081	0.0118
02	0.0208	0.0499	0.0286	0.0447
03	0.0216	0.0407	0.0099	0.0192
04	0.0197	0.0422	0.0099	0.0666
05	0.0200	0.0165	0.0088	0.0258
06	0.0168	0.0190	0.0101	0.0366
07	0.0081	0.0381	0.0108	0.0162
08	0.0092	0.0407	0.0051	0.0568
09	0.0084	0.0324	0.0070	0.0280
10	0.0131	0.0667	0.0085	0.0437

C. Results of Stability Index and Selected Persistent Vegetation Plot

In Wilpattu National Park,

Stability Index for ROI 05 = $\frac{0.0200}{0.0165}$ = 1.2121

Stability Index for ROI 07 = $\frac{0.0081}{0.0381}$ = 0.2126

Since SI is high, ROI 05 has the persistent vegetation plot.

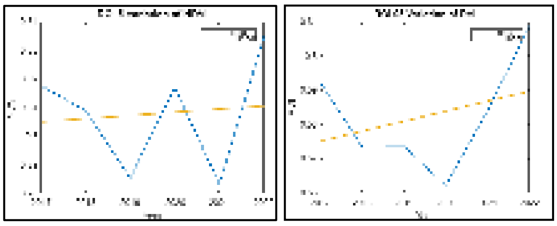

Figure 7: Persistent Vegetation Plots

In Kanneliya Rain Forest,

Stability Index for ROI 01 = $\frac{0.0081}{0.0118}$ = 0.6864

Stability Index for ROI 08 = $\frac{0.0051}{0.0568}$ = 0.0898

Since SI is high, ROI 01 has the persistent vegetation plot.

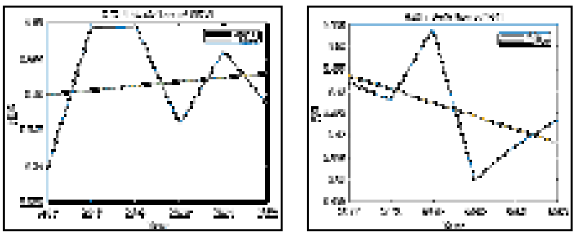

Figure 8: Persistent Vegetation Plots

D. Generated Forest Resilience Indices

By using selected Persistent Vegetation Plots, the scatter plots of NDVI Vs RVI were plotted. Then the outliers were removed and again the scatter plots of NDVI Vs RVI were plotted. The linear regression lines were also fitted.

The gradient of the graph was assigned into weight of NDVI (W1) and the one minus value of gradient graph was assigned into weight of RVI (W2).

The Forest Resilience Indices were generated using the inverse weighted mean method.

Forest Resilience Index = $\frac{(\left(\frac{1}{W1}\right)NDVI+\left(\frac{1}{W2}\right)RVI)}{\left(\frac{1}{W1}\right)+\left(\frac{1}{W2}\right)}$

Forest Resilience Index for Wilpattu National Park,

FRI = (0.7827*NDVI) + (0.2173*RVI)

Forest Resilience Index for Kanneliya Rain Forest,

FRI = (0.7853*NDVI) + (0.2147*RVI)

Using with these indices, we can investigate the resilience of forest to understand how resilient these forests are.

E. Created Maps of Forest Resilience Index

The maps of the Forest Resilience Index were created for both study areas from 2017 to 2022. By comprehensive analysis of these outputs, we can analyze the temporal variability indicating the resilient dynamics of the forests.

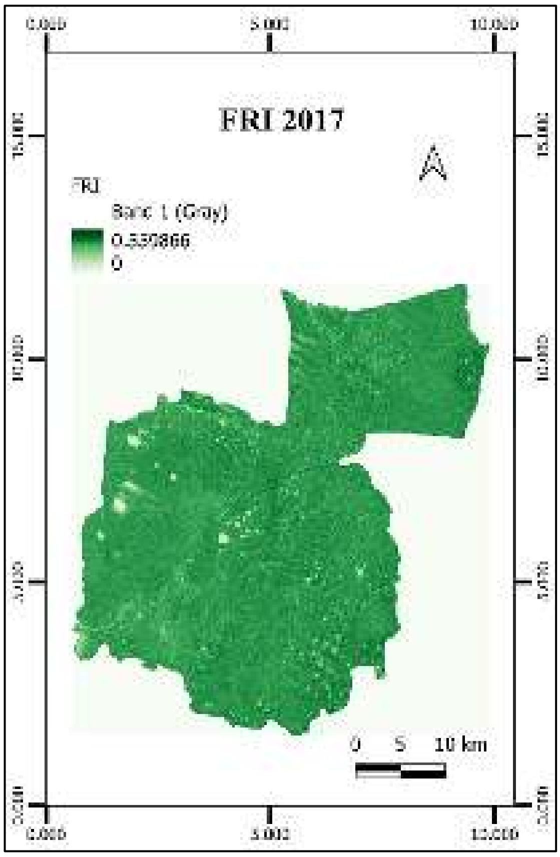

Figure 9 : FRI Map of 2017 in Wilpattu National Park

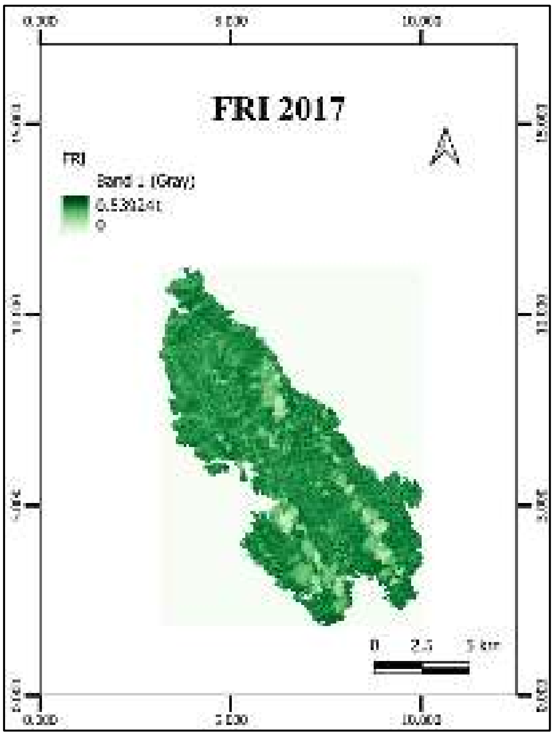

Figure 10: FRI Map of 2017 in Kanneliya Rain Forest

F. Validation

The validation was conducted for an area in the Upper Wilpattu area that fulfilled with trees in 2017 and deforested in 2018. In 2017, the mean value of FRI is 0.3775 and in 2018, the mean value of FRI is 0.3229. Hence we can see in 2017 the area was resilient than 2018.

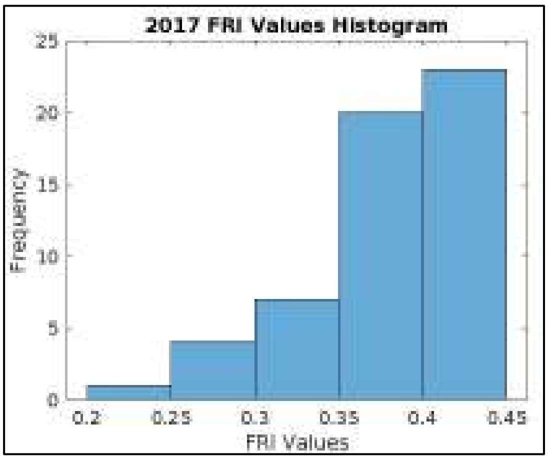

Figure 11: Histogram of FRI Values in 2017

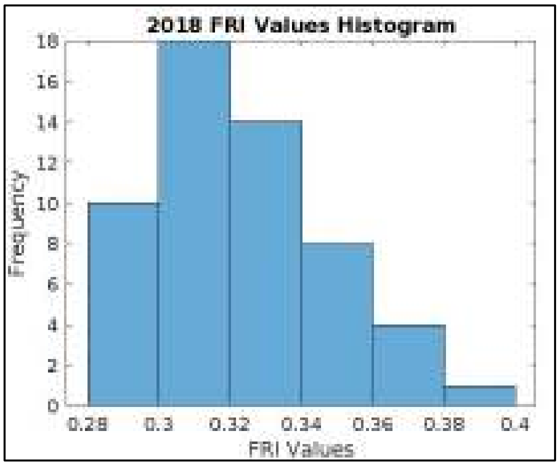

Figure 12: Histogram of FRI Values in 2018

IV. CONCLUSION

Forests are essential for the well-being and health of the planet and its inhabitants. The concept of forest resilience has emerged as a crucial framework to identify how forests respond to disturbances or threats caused by human activities such as deforestation, forest degradation, and climatic changes. Sri Lanka, being one of the main biodiversity hotspots, is home to many significant forest ecosystems. Therefore, it is essential to understand forest resilience for effective forest management and conservation. Accordingly, the research study aimed to estimate the forest resilience of major forests in the Sri Lankan context using Multispectral and Microwave Vegetation Indices. The time series analysis for estimating forest resilience was performed for each study area and the Forest Resilience Index for each study areas were generated by combining the NDVI and RVI. The forest resilience indices were mapped regarding to each forest throughout the study time period, and this analysis helped to analyze the temporal variability indicating the resilient dynamics of the Sri Lankan forests.

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