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Spatio-Temporal Variations in Mangrove Vegetation in conjunction with Related Environmental Factors in Pichavaram (India): 1996-2016

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Abstract-The major objective of the study is to explore the inter-annual vegetation changes of Pichavaram mangroves over two decades (from 1996 to 2016). The study mainly focuses on the summer and onset monsoon season, where the variability in vegetation is easily noticed. Vegetation indices like Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST) and Land Surface Water Index (LSWI) were estimated from the remotely sensed data of Landsat imagery. A comprehensive evaluation of the relationship among the vegetation indices reveals that there is an increase in the area occupied by the mangroves throughout the years. Correspondingly, the area under the mangrove cover have also faced an increase in the surface temperature, but much lesser when compared to the adjacent areas. According to the results obtained, NDVI, LSWI, LST, can be used to understand the status of mangrove vegetation with increase and decrease of temperature and water. It is found that the correlation among the remotely sensed indices depend on the season of the year. The summer season in general exhibited higher negative correlation with NDVI and LST and also between LST and LSWI than the onset monsoon season. It is also apparent that with the passing of years, the correlations among the indices are also found to be increasing. Thus in the global scenario of variable climate change, it is important to monitor the seasonal changes in vegetation, especially mangroves, for their effective conservation.

Keywords*: Remote sensing; Normalized Difference Vegetation Index; Land Surface Water Index; Land Surface Temperature, Mangroves.*

I. INTRODUCTION

Time series vegetation analysis of mangroves in relation to its varying environmental factors are of highest concern in the present scenario of global change worldwide. The changes invariably affect the ecosystem productivity, biome distribution and the precious carbon deposits of the forest ecosystems [1]. The appreciable role of the multi temporal satellite data to monitor the surface observations and their quantification is remarkable in this context. The physical process of monitoring seasonal vegetation changes and the changes in the surface temperature as well as water, with the aid of *in situ* measurements is difficult and time consuming. In addition, most of the major mangrove forests are swampy and inaccessible in terrain. The analytic approach on mangrove research gained momentum on the onset of early 1990s [2, 3, 4] even though descriptive documentation e.g. [5, 6, 7, 8, 9, 10] of the mangroves have been carried out widely in the past by scientists, ecologists and botanists [11, 12, 13, 14, 15 16].

The mangrove ecosystems are unique forest ecosystems characterized by highly specialized vegetation [17]. Hence, vegetation analysis can be considered as the best way to study species composition and structure of plant community. The regional and site-specific functions performed by the mangroves is highly valued and noticeable [18, 19] since they act as a critical buffer zone and plays a vital role in the protection of the shoreline from the major coastal hazards like flooding, erosion, storm, waves and surges, and tsunami. The threats posed to the human safety residing along the shoreline is prone to increased risk. This is due to the reduced mangrove health and area. It can be substantiated with the example of the Indian Ocean tsunami, which affected the Tamil Nadu coast during 26 December 2004 [21, 22, 23]. Another example is that of the 1999 Super cyclone which affected Orissa's 250 km coastline by uprooting majority of the trees in its immediate vicinity and further inland (except the mangrove cover) and the terrestrial trees behind the mangrove vegetation.

But, in negligence to their importance, mangrove areas are under high risk of extinction due to extensive conversion of the mangrove areas to agriculture, aquaculture, fishing and tourism. This may ultimately lead to the release of stored carbon and increase the intensity of global warming and impact other climate change factors [24] like rise in the global sea level [25, 26, 27, 28, 29] and increase in the atmospheric CO_2 concentration [29]. Other major factors affecting the mangrove vegetation and spatial distribution is changes in the precipitation pattern and temperature [30, 31]. Studies show that the global average surface temperature has increased by 0.74^0 C between 1906 and 2005 due to increased greenhouse gas atmospheric concentrations [29]. Climate change is likely to have a substantial impact on mangrove ecosystems [31], where global temperatures are predicted to increase up to 4.8° C by 2081–2100 [32], which adversely affects mangrove species composition, phenology, and productivity. Raise in the atmospheric temperature inhibits the CO_2 assimilation capability of mangroves and increases evaporation rates. As a remedy, efforts are undertaken by WWF with the support from Global Environment Facility (GEF) through UNEP DGEF and in collaboration with a large group of local, national and global partners to understand the threats posed by climate change to mangrove ecosystem and to duly protect them. As part of a broader coastal site-planning process, the selection of adaptation strategies is likely to be adopted, where mitigation actions are to be undertaken to address both non- climate and climatic threats.

Section I introduces the various environmental factors affecting the vegetation of mangroves. Section II describes how remotely sensed data is useful to detect the dynamics in vegetation over the years. Section III describes the methodology used for the execution of present study. Study area chosen for the analysis is also described in detail in this section. Section IV describes the major results and discussion derived from the present study. SectionV describes the conclusions of the study and the scope for future work.

II. RELATED WORK

Remotely sensed time-series data acquired in different spectral bands aid change detection analysis and provide a powerful tool to learn from past events and to monitor current conditions [33]. Since remote sensing techniques makes it easier to collect many samples over a wide region almost instantaneously, the measurement of radiant temperature is much easier than the airborne and space borne platforms [34]. Apart from these, the remote sensing instruments can even collect measurements of red and infrared portions of electromagnetic spectrum, which in turn helps to quantify the variation in vegetation. The resolution of Landsat is sufficient to study the significant spatial and temporal variation in vegetation and surface temperature. The most likely effects of increased surface temperature are expected to affect the mangroves by altering the species composition, phenological patterns like flowering and fruiting. Normalized Difference Vegetation Index (NDVI) is a remotely sensed measure of greenness, which is related to the biophysical (Leaf area Index, Canopy diameter etc.) as well as the phenological changes. It also provides a measure of the vegetation productivity like absorbed Photosynthetic active radiation (PARabs). Thus, analysis of NDVI time series can quantify the recent changes in an ecosystem.

The Pichavaram mangrove falls under the Coastal Ecological Sensitive Areas (ESA). The objective of the present study is (a) To conduct a temporal analysis of LST, NDVI and LSWI using the Landsat satellite imagery (b) to present the impacts of climate change factors on mangrove vegetation (NDVI) at a regional scale, thereby to demarcate the spatial and temporal variations over the highly vegetated areas of mangroves and then to analyze the trends over a period of time (c) to derive the correlation coefficients of site specific NDVI and climate variation (temperature and surface water), mapped regionally on an annual and seasonal basis from 1996 to 2016, to clarify the relationship of vegetation and climate variation especially focusing on post tsunami effects. The paper demonstrates the effective use of remote sensing for deriving the objective measurements of environmental influence on mangrove vegetation.

III. METHODOLOGY

Study area

The Pichavaram mangrove wetlands which lie in between the latitudes of 11º 20' N and 11º 30'N and the longitudes 79º 45' E and 79º 55'E (Figure 1), is one of the major mangroves of Tamil Nadu coast lying between the Coleroon –Vellar estuarine complex in the northernmost region of the Cauvery delta. The entire mangrove vegetation which was declared as a Reserve forest in 1987 covers an area of about 1471 ha including mangrove forests, mud flats, sand dunes and back water. The reserved area is divided into three divisions namely Pichavaram (1055 ha), Killai (327 ha) and Pichavaram RF Extension (89 ha). The area is colonized by 13 true mangrove species [35], mainly dominated by *Avicennia marina* (Forsk.) Vierh. The climate is sub-humid with very warm summer and with an annual average rainfall (70 years) of 1310 mm and annual average rainy days up to 56. The rainfall is received from the northeast monsoon, which hits the Tamil Nadu coast between the months of October and December, and nearly 70% of the rainfall occurs between November and December, which supplies fresh water to the mangrove forests. Thus, the dry season is comparatively longer extending from February to September [35].

Satellite imagery acquisition and analysis

The following Landsat satellite images (Table 1) were downloaded from the official website of Earth Explorer USGS (earthexplorer.usgs.gov) and used as the primary data source for the comprehensive evaluation of the temporal vegetation and the relative factors affecting it over the study area. Cloud free data, one from the summer season and the other from the onset monsoon season for the corresponding year were selected for the analysis. The first step in image pre-processing was the radiometric correction of the image by converting the Digital Number (DN) values to at- sensor radiance (equation 1). After the conversion to radiance values, the thermal infrared band of each data was chosen for the derivation of brightness temperature (equation 2), from which the emissivity (equation 3) was calculated. Land surface temperature (equation 4) was ascertained from the above mentioned steps. The next step was to perform the atmospheric correction using FLAASH in ENVI, from which the spectral reflectance of the images was attained. Atmospheric correction is necessary because the cloud cover affects the sensing ability and increases the DN values of the adjacent pixels. More over the brightness measured from the ground features increases as the clouds scatter the light. From the reflectance image, the Normalized Difference Vegetation Index (equation 6), and the Land Surface Water Index (equation 7) were derived. The Landsat User's Handbook [36] provides the following equations.

$$\text{Radiance} = ((L_{MAX} - L_{MIN}/QCAL_{MAX} - QCAL_{MIN})*(QCAL - QCAL_{MIN})) + L_{MIN} \quad (1)$$

Where,

L_{MAX} = the spectral radiance that is scaled to QCALMAX in W/ (m^2 * sr * m)

L_{MIN} = the spectral radiance that is scaled to QCALMIN in W/ (m^2 * sr * m)

$QCAL_{MIN}$ = the minimum quantized calibrated pixel value (corresponding to LMIN) in DN = 1

$QCAL_{MAX}$ =the maximum quantized calibrated pixel value (corresponding to LMIN) in DN=255 (TM / ETM+)

QCAL = DN

$$BT = K2 / \text{Log}\{(K1/\text{Radiance}) + 1)\} \quad (2)$$

Where, TB = the effective at-satellite brightness temperature in Kelvin

K1 = 774.89 (watts/ (meter^2* ster * µm))

K2 = 1321.08 (Kelvin) are calibration constants;

$$\varepsilon = (1.0094 + (0.047* \text{alog}(\text{radiance}))) \quad (3)$$

The temperature of the land surface, which can be considered as the key factor to determine the surface radiation and energy exchange [41] was estimated through a couple of steps.

$$LST = BT / \{1 + (\lambda * BT/\rho * \log\varepsilon)\} \quad (4)$$

Where,

LST = Land surface temperature

TB = Brightness temperature

λ = Wavelength of emitted radiance (11.5 µm)

ρ = h x c/s =1.438 x 10^{-2} mK

(s=Boltzmann constant=1.38 x 10^{-23}J/K,

h = Planck's constant=6.626 x 10^{-34}Js, c=velocity of light= 3 x 10^8m/s)

ε = Land surface emissivity

The image capture time is 5:30 am in Greenwich Mean Time, which is approximately equal to 10:30 am as per Indian timing. Overall, 40 points were selected randomly over the study area to derive the pixel to pixel correlation between the NDVI, LSWI and LST. The Land surface temperature obtained was in the unit kelvin which was then converted to degree Celsius using the following equation (equation 5)

$$LST \text{ (in Celsius)} = LST \text{ (in kelvin)} - 273 \quad (5)$$

The NDVI was calculated by the formula

$$NDVI = \rho_{NIR} - \rho_{RED} / \rho_{NIR} + \rho_{RED} \quad (6)$$

Where, RED and NIR bands are Band 3 and Band 4 respectively in Landsat 4-5 and also in Landsat 7 and Band 4 and Band 5 in Landsat 8. Normally, the NDVI values ranges between -1 to +1. The negative values indicate a non-vegetated area and a positive value indicates a vegetated area. Higher the NDVI values, higher the vegetation cover. Based on this mangrove forests were discriminated as **Highly Dense Mangrove**, **Dense Mangrove**, **Moderately Dense Mangrove**, **Sparse Mangrove** and O**ther Vegetation**, which includes other terrestrial crops and mudflats. The Land Surface water index was derived using the following equation (equation 7). Finally, the correlation among the three main indices were studied and also individual maps were prepared.

$$LSWI = (\rho_{NIR} - \rho_{SWIR}) / (\rho_{NIR} + \rho_{SWIR}) \quad (7)$$

IV. RESULTS AND DISCUSSION

Times series dynamics in mangrove vegetation from 1996 to 2016 in conjunction with its environmental factors

Summer season as well experienced by the least favorable climatic conditions for the vegetation growth, experiences a decreased NDVI rate when compared to the onset monsoon season (figure 2 & figure 3 respectively). The raise in temperature of the air and the soil which in turn causes higher evapotranspiration in plants and ultimately a decrease in the amount of water present in the soil are the major adverse effects faced by the mangrove community during this season. From the resultant classified NDVI images of this study, it is apparent that there is a voluminous increase in the mangrove area from the past scenario to the present. It can be substantiated that the areas falling under the sparse, moderate and dense mangroves were slowly converted to the highly dense mangrove region by 2016. The abrupt decrease in the NDVI that is visible in the 2005 image can be attributed to the natural calamity- Tsunami, which adversely affected the Tamil Nadu coasts during the year 2004 in December. While the temperature raise is taken into consideration, it can be inferred that, with the overall raise in temperature worldwide, the mangrove area was also not exempted from temperature raise but comparatively lesser to the adjacent areas. Earlier in 1996, the denser mangrove region which exhibited a surface temperature range of 26-28^0 C were transformed to a higher temperature range of 28-30^{0}C in 2016. The other vegetation areas and sand dunes even exhibited a higher range of 30-32^{0}C at 10:30 am during 2016.

The results of the surface water content analysis of the Pichavaram mangroves revealed that their variation throughout the years were in accordance with the variation in vegetation and vice versa. The dense mangrove regions were established in areas exhibiting higher water content (LSWI) of 0.4 to 0.6. With the increase in the extent of the mangrove area, the regions possessing a higher surface water content were also found increased. From 1996 to 2016, the area under the mangrove cover is proven to be increased and hence the area under the surface water also during the summer season, reaching to a maximum LSWI range of 0.6 to 0.8. In 2005, there has been a greater extend in the surface water mainly due to the post tsunami effects. 2009 image clearly demarcates the water index of the lesser vegetation from that of the moderately vegetated ones and that of higher vegetation.

This highlights the application of remote sensing and GIS in monitoring the natural disasters over inaccessible and vast regions like mangroves. The credit completely goes back to the effective efforts undertaken by the state and the private managements to bring up more mangrove plantations in the tsunami-affected area there by to create a larger extend of the forest in future. Slowly the mangrove areas were restored back to their original health status and even more with the years. Studies prove that 500 hectares of mangrove area was clear felled between 1935 to 1970, in Pichavaram mangroves [37], which further declined till early 1990’s. As an extension of the management practices, Joint Mangrove Management Programme at national level [38] was implemented, through which the rapid recovery of about 250 ha of mangrove area was effected with the aid of State Forest Department and Non-Government Organization [35, 38]. While the area wise distribution of Pichavaram mangroves is considered, studies show that even though from 1930-1994 the mangrove area decreased from 1165 ha to 411 ha, there had been an increase in the area to 941 ha over the following 18 years, that is, from 1994-2011 [39]. The restoration of mangrove area was initiated by JMM programme (Joint Mangrove Management).

The onset monsoon and the monsoon season are considered as the most favorable seasons for the vegetation growth and establishment. This is well substantiated from the resultant images of the study, where the dense mangrove region in 1996 is found to be increased to the level of highly dense mangrove during 2016. Simultaneously, the moderately dense mangroves were converted to the range of dense mangrove. The temperature of this season was much lesser than the summer season. In 1996, the mangrove areas experienced a lesser temperature of 22-24^{0}C, which gradually increased to a range of 24-26^{0}C along the dense mangroves and the sparse mangrove and sand dunes possessing a temperature range of 26-32^{0}C. Throughout the years, there has been an appreciable decrease in the LSWI ranges during this season. The mangrove regions of higher LSWI ranges of 0.6 to 0.8 seems to be decreased by the passing of years to a lower range of 0.4 to 0.6. The classified images of variations in the vegetation and climatic factors are illustrated below.

Maximum NDVI values in relation to its prevailing environmental conditions

Highly correlated environmental factors with the Maximum NDVI values were estimated and tabulated (Table 2). In the year 1996, during the summer season, at a land surface temperature of 26.2 ^{o} C, and with a water index of 0.46, the highest value of vegetation index of 0.70 was observed. Similarly, for onset monsoon, the most favorable temperature and water index were 20.6^{o}C and 0.50 respectively for a maximum of 0.73 NDVI. Nine years later, even though the temperature has raised to 24^o C, the water index has also raised to 0.55, which favorably lead to a further increase in the NDVI to 0.78 in the onset monsoon season of 2005.

At the same time, the post tsunami effect is well evident on the 2005 summer image where the Maximum NDVI has fallen to 0.39. The fact that the mangrove areas displayed a higher water index of 0.58 in 2005 is because the area was fully laden with water, making the land surface even cooler, which attributed to be 24.5^{o}C. As mentioned earlier, due to the effective mangrove restoration activities by the state forest department and M.S. Swaminathan Research Foundation, there had been a drastic increase in the mangrove vegetation, which can be evidently interpreted through the sudden raise of NDVI to 0.66 in summer and 0.78 in onset monsoon during 2009. In 2016, the NDVI has further raised up to 0.75 in summer and 0.85 in post monsoon. With the overall raise in temperature worldwide, the land surface temperature over the mangrove region has also increased. Likewise, the increase in the land surface water in 2005 from 1996 can be attributed to the 2004 tsunami. When the overall situation is taken to consideration throughout the years, the water level seems to be decreased from that of 1996, both in the summer season as well as in the onset monsoon. This proves that with the increase in temperature, the water index of the region had ultimately fallen. Same should have been the fate of mangrove vegetation unless for the restoration activities.

Dynamics in mangrove vegetation cover of Pichavaram

Further, an attempt was made to quantify the overall vegetation changes that had taken place over Pichavaram mangrove ecosystem with the passing of years. To serve the purpose, values of the vegetation indices were taken along a particular region, having the same latitude and longitude (Table 3). The below table refers the vegetation indices over the latitude 11.429124^o N and the longitude 79.794071^{o}E. The table clearly depicts that at a particular region of densely vegetated mangrove (having same latitude and the longitude) there has been a considerable increase in all the vegetation indices over a period in that particular region. During the summer season, the NDVI value was 0.5 in 1996, which later decreased to 0.27 in 2005. The reason behind it could be clearly traced back to the occurrence and the effect of Tsunami, which hit the Tamil Nadu coast on December 2004. Then in 2009 summer, there was a raise in NDVI to 0.63 and recently in 2016, it had sharply shoot up to 0.74. Similar is the case with the pre-monsoon season where a considerable increase in NDVI has occurred from 0.65 in 1996 to 0.82 in 2016. Simultaneously we can see a gradual increasing trend in the NDVI and LST over that particular region of interest, whereas the land surface water shows a decreasing trend.

Overall variation in the mean mangrove vegetation over the study area

On an average, the mean values of NDVI, LST and LSWI had achieved a gain throughout the years (Table 4). In general, lower NDVI values are observed during the summer season and higher NDVI values are seen during pre-monsoon (September) for all the years for dense vegetation. However, the variability between summer and winter mean NDVI is not high. However, NDVI values for green vegetation is higher, the minimum-maximum temperature range is lower i.e. the region is cooler and the area exhibit higher NDVI values throughout the year for dense vegetation (> 0.50) with maximum NDVI reaching 0.80. The mean temperature variation is well noticeable (~21^{o}C to ~29^{o}C) throughout the year and water is more during the onset monsoon season. The scale of the monthly NDVI changes over time is a key sign of the contribution of vegetation presence activity in different months to total yearly vegetation growth. Similarly, higher values of LSWI are noticeable during the pre-monsoon season with a mean ranging from 0.38 to 0.45 where as a lesser LSWI range of 0.26 to 0.43 is noted in the summer season. The exceptional very high value of LSWI of 0.46 during 2005 may be affected due to tsunami. The NDVI patterns coupled with the climatic variables can be utilized for futuristic studies also.

Correlation among the remotely sensed indices

To analyze the effects of regional climatic changes on NDVI of dense vegetation, Pearson product-moment correlation between NDVI–LST, NDVI–LSWI and LST–LSWI were explored. The drastic variation that had happened among the vegetation conditions and the various environmental factors were thus analyzed and are represented as follows. The condition of the mangroves that was prevailing in the past (1996) is compared to that of the present situation (2016). As expected, the correlation between the vegetation index and the surface temperature was negative i.e. it displayed a decreasing trend with the raise in temperature in both the seasons (Table 5). While comparing within the years, during summer season the negative correlation from 1996 is observed to be increased by the year 2005 and further raised in the year 2016. Thus it can be established that within the study area, the regions having a higher land surface temperature exhibited a comparatively lower NDVI and vice versa. The relationship between the water index and the vegetation index was also displaying a trend as expected. The higher value 0.9 of LSWI in summer 1996 was found to have a decrease in the year 2005 from which it slightly rose to 0.8 in 2009 and in 2016 it further decreased to 0.7. Throughout the years we can thus conclude that there is an appreciable decrease in the value of LSWI from 0.9 to 0.7 from 1996 to 2016 in the summer season.

The same trend is observed among all the three parameters during the onset monsoon season also. The negative correlation between the NDVI and LST is found to increase from -0.6 to -0.3 in the year 2005, which again slightly fell down to -0.5 in 2009 and strongly raised to -0.1 in 2016 September. In contrast to the summer season, the correlation between the NDVI and LSWI is found to increase throughout the years in the pre monsoon season. The raise in correlation from 0.5 in 1996 to 0.78 in 2005 is well observed in the table sited above from which it showed a leap to 0.9 Correlation in 2009 and then decreased to 0.83 in 2016. Hence the assessment can thus be made that the overall correlation between the vegetation index and the water index from the past to the present has undergone an increase overall. The adverse effect of the land surface temperature on surface water is well remarkable and is not yet exempted in the season of pre monsoon also. From 1996 to 2005, the negative correlation among these parameters has risen from -0.4 to -0.3. That again further decreased to -0.6 in 2009, finally rising to -0.3 in 2016. From these observations also, it can be proven that with the raise in temperature, the surface water decreases.

Studies reveal that the slope of NDVI versus LST to be negatively correlated to Crop-Moisture Index [40]. The slope of LST vs NDVI can also be related to the evapotranspiration rate of the surface [41, 42]. Higher temperature results in increased evapotranspiration which in turn decreases the soil moisture and thereby a decline in the NDVI, while it can be estimated that a transpiring canopy is cooler [16] because dense vegetation induces more evapotranspiration and thereby lowers the LST [42, 43, 44]. But, in contrast, studies even show positive correlation between NDVI and LST in the northern latitudes [45].

V. Conclusion and Future Scope

Thus to conclude, we can summarize that the Pichavaram mangrove vegetation is affected by the climatic and seasonal variations. The NDVI and LST showed a negative correlation with each other, whereas the vegetation index is positively related to the water index. It is well evident from our study that even though the adjoining land areas are facing a problem of accelerated raise in the land surface temperature and a decrease in the land surface water component, the mangrove areas have exhibited an area wise and density wise increase, which ultimately resulted in an increased NDVI rate. Since the vegetation increased, the surface area has become much cooler, reducing the evaporation of water from the surface soil, which finally resulted in an increased surface water amount even though the surface temperature has risen with the pace of the global temperature raise. It can also be mentioned that the availability of sufficient rainfall and fresh water flow, accompanied with drought less years from 1994 onwards could be other major reason for the increase in the vegetation index NDVI. The influence of thermodynamics and hydrodynamics can be well studied during the upcoming years also as global warming has emerged as a serious issue in the present scenario. This in turn the study would turn out to be a nugget of information for the management planners and the social workers for improved restoration activities. Similar studies could be applicable to the urban areas also, where LST, LSWI, and NDVI can be considered as the three basic indices to estimate the ecological environment and there exists a strong correlation among the three indices thus making us possible to evaluate the environmental factors with the aid of remote sensing and GIS.

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Figures and Tables

Table 1: Landsat images having relatively less cloud cover which were used for the study

Sl no	Summer	Onset Monsoon	Sensor	Path & Row
1	18-05-1996	23-09-1996	Landsat_5	142/52
2	11-05-2005	16-09-2005	Landsat_5	142/52
3	06-05-2009	11-09-2009	Landsat_5	142/52
4	02-04-2016	09-09-2016	Landsat _8	142/52

Table 2: Maximum NDVI and its corresponding favorable climatic parameters

SUMMER				ONSET-MONSOON			
DATE	NDVI	LSWI	LST	DATE	NDVI	LSWI	LST
18-05-1996	0.7029	0.4617	26.2706	23-09-1996	0.7387	0.501	20.6363
11-05-2005	0.3993	0.5886	24.5832	16-09-2005	0.785	0.5507	24.1334
06-05-2009	0.6633	0.4559	18.4147	11-09-2009	0.7838	0.4866	22.5183
02-04-2016	0.7592	0.4849	29.07	09-09-2016	0.855	0.4934	25.7686

Table 3: Variations in the vegetation indices over a particular region of interest [11.429124ºN latitude and 79.794071ºE longitude]

SUMMER				ONSET-MONSOON			
DATE	LSWI	LST	NDVI	DATE	LSWI	LST	NDVI
18-05-1996	0.2564	27.1156	0.5135	23-09-1996	0.4718	21.5199	0.6529
11-05-2005	0.4155	25.4335	0.2782	16-09-2005	0.3995	24.5638	0.6817
06-05-2009	0.4004	19.6608	0.6353	11-09-2009	0.4432	22.9198	0.7208
02-04-2016	0.4578	29.9592	0.7402	09-09-2016	0.4492	25.9031	0.8283

Table 4: Mean (μ) ± standard deviation (σ) of NDVI, LST and LSWI

ONSET-MONSOON			
DATE	LSWI	LST	NDVI
23-09-1996	0.38 (± 0.14)	21.05 (± 0.48)	0.54 (±0.18)
16-09-2005	0.45 (± 0.06)	24.06 (± 0.52)	0.67 (± 0.09)
11-09-2009	0.41 (± 0.08)	22.87 (± 0.78)	0.68 (± 0.10)
09-09-2016	0.43 (± 0.05)	25.63 (± 0.53)	0.80 (± 0.04)
SUMMER			
DATE	LSWI	LST	NDVI
18-05-1996	0.26(± 0.15)	27.01 (±1.08)	0.45 (± 0.19)
11-05-2005	0.46 (± 0.07)	25.02 (± 0.48)	0.27 (± 0.10)
06-05-2009	0.37 (± 0.08)	18.48 (± 1.50)	0.56 (± 0.07)
02-04-2016	0.43 (± 0.05)	29.17 (± 0.85)	0.69 (± 0.04)

Table 5: Pearson product-moment correlation coefficient between NDVI, LST and LSWI

SUMMER (1996-2016)			
Date	NDVI vs LST	NDVI vs LSWI	LSWI vs LST
18-05-1996	-0.74	0.90	-0.72
11-05-2005	-0.21	0.76	-0.37
06-05-2009	-0.15	0.86	-0.30
02-04-2016	-0.10	0.78	-0.26
ONSET-MONSOON (1996-2016)			
Date	NDVI vs LST	NDVI vs LSWI	LSWI vs LST
23-09-1996	-0.65	0.59	-0.48
16-09-2005	-0.38	0.78	-0.38
11-09-2009	-0.57	0.90	-0.65
09-09-2016	-0.12	0.83	-0.34

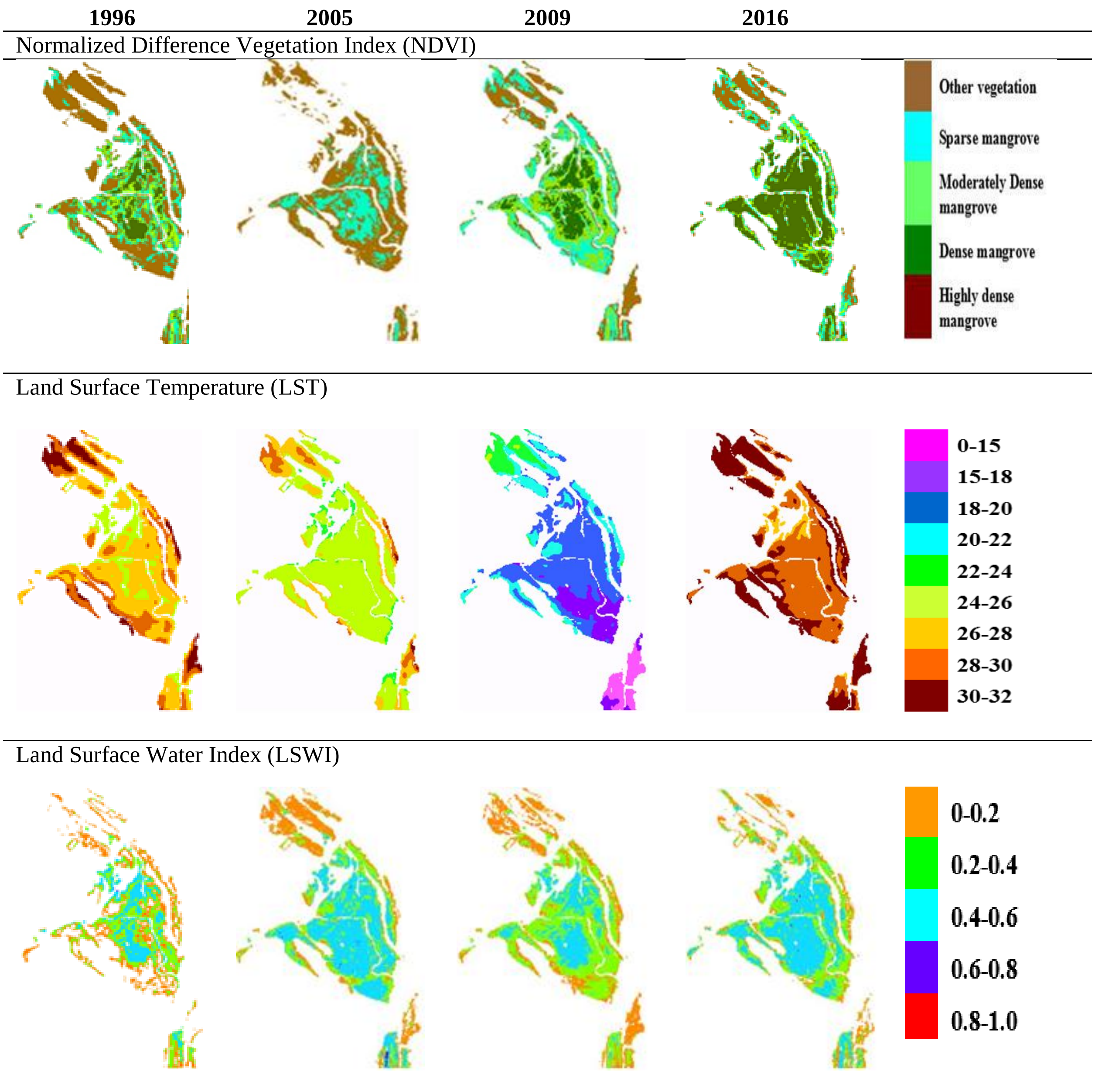

Figure 2: Dynamics in NDVI, LST and LSWI of Pichavaram over the decades for summer season

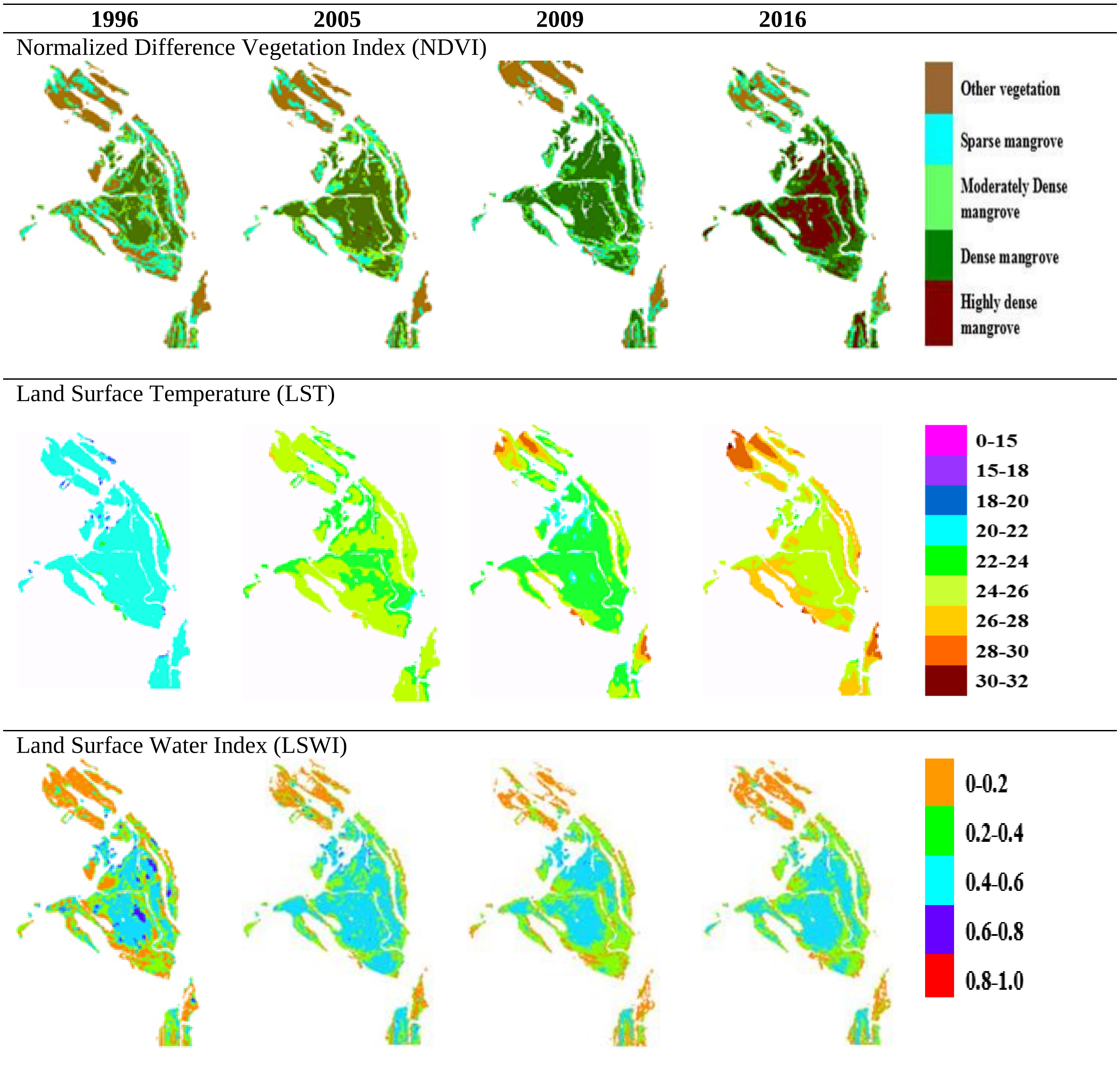

Figure 3: Dynamics in NDVI, LST and LSWI of Pichavaram over the decades for onset monsoon season

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