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RESEARCH ARTICLE

Analysis of Seasonal Vegetation Dynamics Using MODIS Derived NDVIand NDWI Data: A Case Study of Tamil Nadu

Prajesh*,P.J., Balaji Kannan, Pazhanivelan, S, Kumaraperumal, R, and Ragunath, K.P.
Department of Remote Sensing and GIS, Tamil Nadu Agricultural University, Coimbatore - 641003

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ABSTRACT

Temporal and spatial variations in vegetation distribution and growth require continuous evaluation of land use and land cover change detection. With an objective to assess and utilize spatially derived vegetation indices viz., NDVI and NDWI over the land use and land cover, the seasonal vegetation dynamics were analyzed for the state of Tamil Nadu during the 2017 Kharif and Rabi season. The NDVI and NDWI showed a good range of temporal variations in vegetation biomass condition and crop water conditions, however, NDVI valuesappear to have increasing variations when compared to NDWI values. The study highlighted that, based on the mean, maximum and minimum values of NDVI, the highest variation were noticed over the swamp forest irrespective of the season. However, the percentage of variation was noticed to be higher during Rabi season (94.28) when compared tothe Kharif season (37.64) within the swamp forest. While based on NDWI statistical values, the coefficient of variation was noticed to highest in plantation land (66.32) during Kharif season and 43.02 per cent in cropland during Rabi season. Based on the study, within the forest ecosystem, the variation in vegetation greenness and crop water stress response were found to be least during both the season.

Keywords: *NDVI, NDWI, Vegetation, Land Use and Land Cover, MODIS*

INTRODUCTION

The presence of incredible diversity found at the global scale has made an accurate representation of terrestrial vegetation in the Earth System model to be a continuing challenge. Vegetation response to the range of climates, geomorphological substrates, natural disturbance and human encroachments has been noticed globally with an incredible array. A realistic measure of existing land cover is necessary wherein utilizing remote sensing driven tool provides with new global level vegetation classification (Townshend *et al.,* 1991). In the past decision makers and researchers employed one indicator or index because that was the only measurement available to them, or there waslimited time available to acquire data and compute derivative indices or other deliverables. However, in the recent years, there has been a strong global interest and growth in the development of new indices based on various indicators that are suitable for different application and scales (Richter *et al.,* 2008; Nemani *et al.,* 2009).

Incorporating the optical remote sensing data, various vegetation indices have been developed based on visible and infrared regions of the electromagnetic spectrum to understand and monitor the behavioural changes within the vegetation due to the multispectral bands sensitivity to biophysical parameters of vegetation such as chlorophyll content, water content and internal leaf structure. Tucker (1979) suggested the use of NDVI for assessing the vegetation health and density which reflected the vegetation vigour, percentage of green cover, leaf area index, and leaf biomass. However, studies showed the interpretation of stressed and damaged crops using NDVI was more suitable for in homogenous terrain (Singh *et al.,* 2003). Schmidt and Karnieli (2000) documented the seasonal variability of vegetation over the semi-arid environment and correlated NDWI as a direct discretion of stress that prevails over vegetation during a particular period. Gilabert *et al.* (2002) assessed the generalized soil-adjusted vegetation index using Landsat images. From the images, NDVI, PVI, SAVI, TSAVI, and MSAVI indices were developed.

The present study concentrates on identification and mapping of the spatial distribution of vegetation growth during the cropping seasons in the state of Tamil Nadu which is essential for resource management and planning. While the GIS-derived

*Corresponding author's e-mail: iamprajesh17@gmail.com

sophisticated software was integrated with remote sensing data to provide monitoring of vegetation (Lambin *et al.,* 2001). Since, vegetation is one of the invaluable natural resource which changes spatially-temporally in its extent and distribution, the main objective of this article is to analyze the vegetation change based on the crop greenness indicator (NDVI) and crop water stress indicator (NDWI).

MATERIAL AND METHODS

Study Area

Tamil Nadu is situated in the South-Eastern part of the Indian Peninsular region that lies between 8.5° N and 13.35° N latitude and 78.35° E and 80.20° E longitude (Fig.1). The physiography of Tamil Nadu can be divided into four zones viz., Eastern Ghats, Western Ghats, Coastal Plains and the Central Plateau. The north western, western and southern parts are hilly and rich in vegetation while the eastern parts are fertile coastal plains and northern parts comprise a mix of hills and plains. The central and the south-central regions are arid plains that receive less rainfall than other regions.

The mean minimum and mean maximum temperature ranges from 23.4°C to 33.8°C respectively. The entire Tamil Nadu is divided into 7 agro-climatic zones *viz.,* North Eastern Zone, North Western Zone, Western Zone, Southern Zone, High Rainfall Zone, Hilly Zone and Cauvery Delta Zone. The average rainfall is 945 mm in which North-East monsoon contributes 48 per cent of rainfall while 32 per cent is contributed from the Southwest monsoon (Gumma *et al.,* 2014).

Land Use and Land Cover

The extraction of the geographical areas under different LULC classes provides a basic idea about the productive and non-productive regions and lands of Tamil Nadu. The LULC based was generated using IRS PAN Sharpened based LISS III image at 1:50,000 scale generated by the Department of Remote Sensing and GIS, TNAU, Coimbatore, India.

Based on the Land Use and Land Cover map, a wide range of biomes exists in Tamil Nadu (Fig. 2) that extends east from the Western Ghats, mountain rain forests inthe Western Ghats through the Deccan plateau, dry deciduous forest cover (8684.932 sq. km) and Deccan thorn scrub forest (2559.80 sq. km) to tropical dry broadleaved evergreen forests (5434.104 sq. km) and then to wetland that are either natural or manmade (947.958 sq. km), swamp (166.525 sq. km) and mangrove located towards the Bay of Bengal.

In terms of agricultural land cover, Rabi cropland occupies a major area (13630.054 sq. km) when compared to Kharif cropland (5232.520 sq. km). A diversification in form of animal husbandry, non-food crops, horticulture, floriculture, sericulture and plantation (9067.513 sq. km) which consist of agricultural, horticultural plantation crops and mix of agro -horti plantation crops is also seen. However, that also remains an enormous area under degraded wasteland (5361.469 sq. km) which are mostly salt-affected land or ravenous land formed due to the process of erosion. While the built-up areas that consist of residential land, reclaimed lands, and lands for mining purpose, transportation and industrial areas yoccupy 5291.638 sq. km of total area.

Cropping Seasons

Cropping season in Tamil Nadu is classified into two main seasons based on monsoon (i) Kharif (ii) Rabi. The Kharif cropping season is from July-October during the South-West monsoon and the Rabi cropping season is from October-March (winter) during the North-East Monsoon period. In Tamil Nadu, the principle food crops include rice, maize, jowar while the major cash crops in Tamil Nadu include cotton, sugarcane, oilseeds. Banana and mangoes are the most important horticultural product grown in the state.

Kharif crops are sown during May or June andstart with the onset of South-West monsoon over Tamil Nadu. Rabi crops are sown around mid-October, preferably after the south east monsoon and are grown with rainwater received from the North-East monsoon that has been percolated into the ground or using irrigation system (Nathan, 1998).

Data Processing

The data set was downloaded for a period between June 2017 to December 2017 which corresponds to Julian days between 153 and 361. MODIS on-board terra sensor surface spectral reflectance product (MOD09A1) was downloaded from the NASA developed earth data website (http://search.earthdata.nasa.gov). The terra-based sensor that provides multispectral, temporal and angular data for medium to coarse resolution land cover characterization was captured as h25v7 and h25v8 gridded tiles for entire Tamil Nadu at 500-meter spatial resolution and at 8-day temporal resolution. The two tiles (h25v7 and h25v8) were mosaicked, reprojected from sinusoidal projection to Transverse Mercator projection and subsetted for the extent of Tamil Nadu using MODIS Reprojection Tool (MRT).

Extraction of Vegetation Indices

Inter annual variations of vegetation index values were considered for estimating the variations due to weather fluctuation and the ecosystem component. The extraction of vegetation index values was done using raster calculator based on the equation 1 and equation 2 for NDVI (Normalized Difference Vegetation Index) and NDWI (Normalized Difference Water Index) respectively, wherein the values were represented in a value scale between -1 to 1.

NDVI :	NIR-Red / NIR+NIR	...Equation 1
NDWI :	NIR – SWIR / NIR + SWIR	...Equation 2

Considering the huge number of raster datasets (NDVI and NDWI) that was generated from the MOD09A1 product, manual processing using the raster calculator becomes a time-consuming task. Hence, to automate the process of NDVI and NDWI extraction, Model Builder in Arc GIS 10.1 was utilized. For assessing the season based crop condition assessment, individual dated NDVI raster and NDWI raster were grouped into monthly raster datasets using maximum cell statistics and then rearranged into season wise *viz.,* Kharif season (June to September) and Rabi season (October to December) using a python script.

In order to estimate the area showing vegetation greening or browning and understand the deviation of minimum and maximum ranges of NDVI and NDWI values, the vegetation index values were reclassified and categorized into five classes *viz.,* less than 0, 0.0 to 0.2, 0.2 to 0.4,,0.4 to 0.6 and 0.6 to 1 where each range depicted the condition of vegetation biomass and water availability within the crop. The reclassified images were subjected to zonal statistics and zonal histogram using land use shapefile of Tamil Nadu.

RESULT AND DISCUSSION

Seasonal Averaged NDVI Profile

To derive the seasonal NDVI (Fig.3) and NDWI (Fig.4) variations, the zonal averaged NDVI and NDWI (maximum) and zonal averaged NDVI and NDWI (minimum) values was carried out for the various land cover categories *viz.,* forest, cropland (Kharif), cropland (Rabi), plantation land, scrubland and swamp forest of Tamil Nadu.

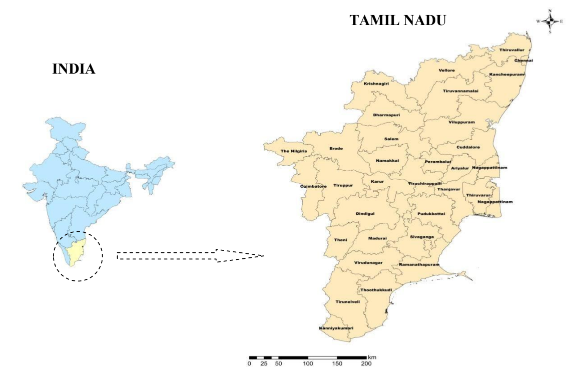

Fig. 1. Study Area Location Along with District Boundaries

During the Kharif season (Table I), maximum NDVI (NDVImax) is observed under forest area (0.91) and the minimum NDVI (NDVImin) is observed under

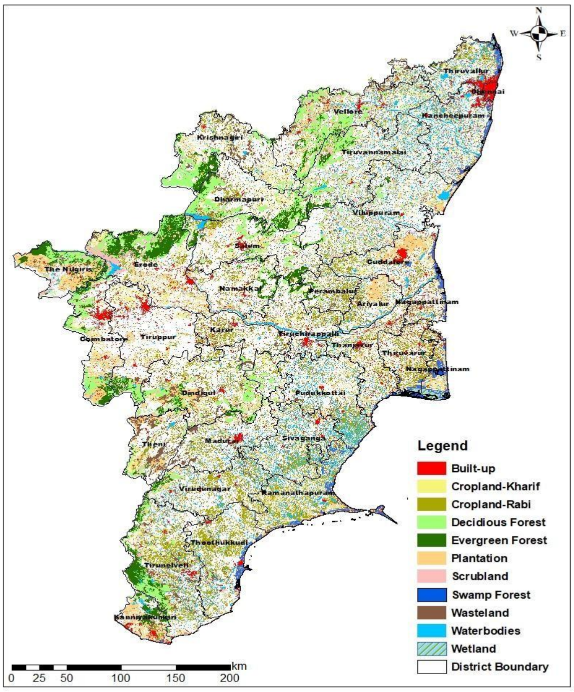

Fig. 2. Land Use and Land Cover Map of Tamil Nadu

swamp forest areas (0.03). In the case of cropland (Kharif) area, NDVI varied from 0.14 (NDVImin) to 0.85 (NDVImax). A similar variation of NDVI is observed for plantation land, where NDVImax is observed as 0.84 and NDVImin is observed as 0.17. The mean NDVI value is recorded highest for the forest (0.71) followed by scrubland (0.6), while the swamp forest shows the least mean NDVI (0.35).

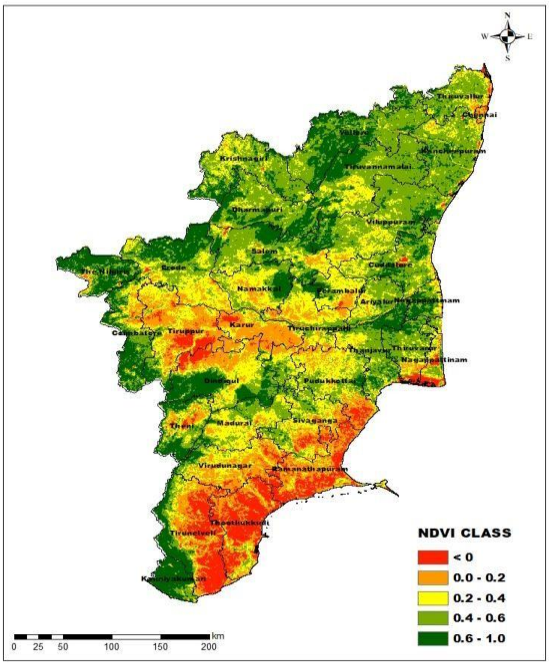

Fig. 3a. Zonal Averaged NDVI classes during *Kharif* Season

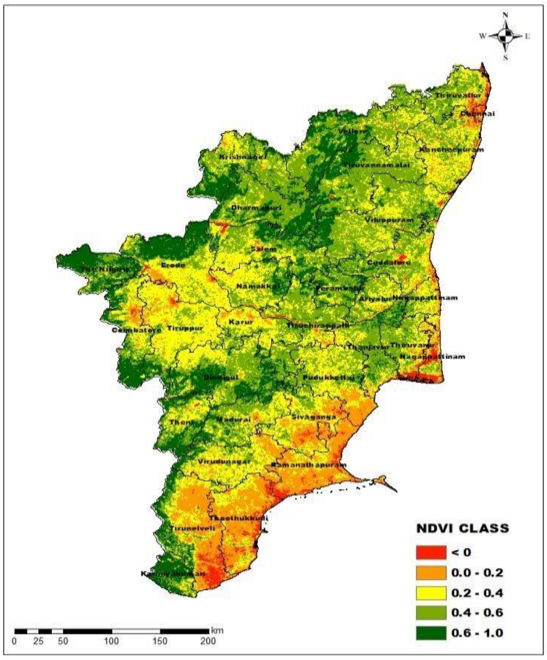

Fig. 3b. Zonal Averaged NDVI classes during *Rabi* Season

Fig 3. Zonal Averaged NDVI Classes Distribution in Tamil Nadu During Cropping Season of 2017

The occurrence of maximum NDVI in the forest might be due to the presence of perennial trees and natural vegetation while the variation in cropland (Kharif) can be due to the type of crops cultivated during the Kharif season (Traore *et al.,* 2014). The coefficient of variation (CV) (Table I) is recorded highest for swamp forest (37.64 per cent), while the lowest CV was recorded for the forest (12.67 per cent), thus representing a constant vegetation development in forest area and indicating that the risk of getting poor vegetation condition is least. While the cropland (Kharif) displayed a lower CV value (19.08) which showed a lesser risk of poor vegetation growth during the Kharif season of 2017. This shows that the inter-seasonal variability is relatively minimized in forest and cropland as a result vegetation growth is relatively stable and remains unaffected by the environmental factors (Mora and Arriagada, 2016).

During the Rabi season (Table I), maximum NDVI (NDVImax) is observed under forest area (0.90) and the minimum NDVI (NDVImin) is observed under swamp forest areas (-0.09). The occurrence of maximum NDVI in the forest can be attributed to the presence of perennial trees and natural vegetation (Traore *et al.,* 2014). For cropland (Rabi) and plantation land, NDVImax (0.84) is observed to be constant. The mean NDVI value is recorded highest for the forest (0.76) followed by scrub forest (0.68), while the swamp forest shows the least mean NDVI (0.30). The NDVI fluctuation in Rabi season for

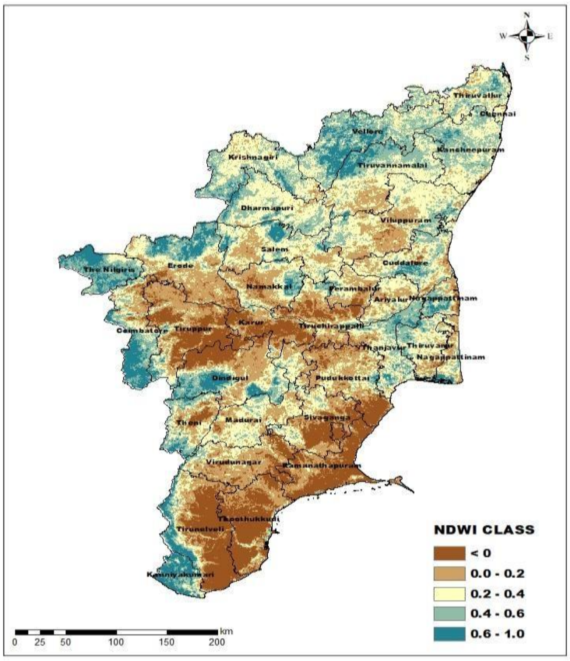

Fig. 4a. Zonal Averaged NDWI classes during *Kharif* Season

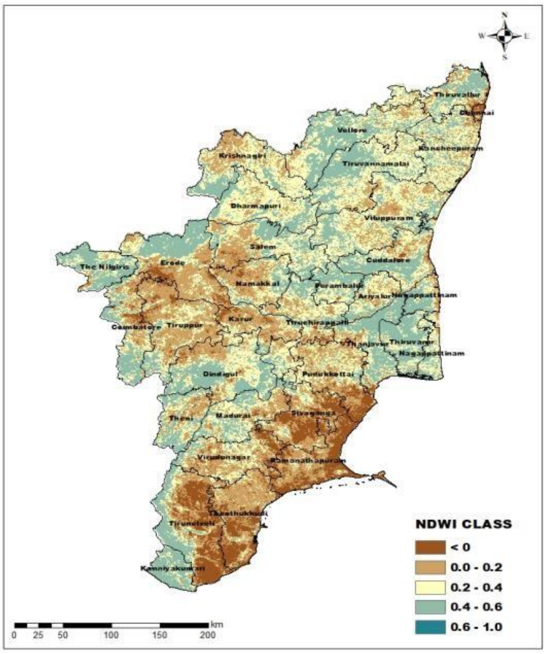

Fig. 4b. Zonal Averaged NDVI classes during *Rabi* Season

Fig 4. Zonal Averaged NDVI Classes Distribution in Tamil Nadu During Cropping Season of 2017

the forest is found to be more sensitive compared to Kharif season that can be related to vegetation health and high biomass development during Rabi season (Huete *et al.,* 2002).

The coefficient of variation (CV) (Table I) is recorded highest for swamp forest (94.28 per cent) which may be attributed to the growth of dense vegetation in some pockets of swamp forests and the lowest CV is recorded for the forest (8.47 per cent), thus representing a constant vegetation development in forest area. The cropland (Rabi) showed a CV value of 19.04 per cent and the plantation land shows a CV value of 14.79 per cent. In case of plantation land and scrub forest the CV is observed to be 14.79 per cent and 13.94 per cent which shows a minimum inter-seasonal variation under these land covers.

Table I. Zonal Averaged NDVI of Land Covers in Tamil Nadu during the Kharif and Rabi season

***Kharif* Season**					
Land Cover	**Minimum**	**Maximum**	**Mean**	**Standard** Deviation	**Coefficient of** Variation
Cropland	0.14	0.85	0.52	0.1	19.08
Plantation Land	0.17	0.84	0.56	0.12	22.02
Forest	0.25	0.91	0.71	0.09	12.67
Scrubland	0.17	0.91	0.60	0.13	21.54
Swamp Forest	0.03	0.72	0.35	0.12	37.64
***Rabi* Season**					
Land Cover	**Minimum**	**Maximum**	**Mean**	**Standard** Deviation	**Coefficient of** Variation
Cropland	0.05	0.84	0.57	0.11	19.04
Plantation Land	0.17	0.84	0.63	0.09	14.79
Forest	0.35	0.90	0.76	0.06	8.47
Scrubland	0.11	0.88	0.68	0.10	13.94
Swamp Forest	-0.09	0.71	0.30	0.17	94.28

Overall it is noticed that irrespective of the season (Kharif and Rabi) the CV value for swamp forest is recorded the highest and the CV value for the forest is recorded the lowest. However, the cropland (Kharif and Rabi) shows almost similar inter-seasonal variability during both the season. This little variation in the croplands during Kharif season and Rabi season may attribute to the abrupt climatic changes that influence the vegetation growth (Hussein *et al.,* 2017).

Seasonal Averaged NDWI Profile

During the Kharif season (Table II), maximum NDWI (NDWImax) is observed under swamp forest (0.57) and the minimum NDWI (NDWImin) is observed under swamp forest areas (0.03) and scrubland (-0.03). Inthe case of cropland (Kharif) NDWI varied from -0.14 (NDWImin) to 0.39 (NDVImax), while for plantation land NDWI varied from -0.14 (NDWImin) to 0.41(NDWImax). The mean NDWI value is recorded highest for the forest (0.24) followed by swamp forest (0.20), while the cropland (Kharif) shows the least mean NDWI (0.13). The maximum mean of NDWI value in the forest might be due to the presence of perennial trees and natural vegetation while the high variation of NDWI values in cropland can be due to the type of crops cultivated in Kharif season (Traore *et al.,* 2014).

The coefficient of variation (CV) (Table II) was recorded highest for plantation (66.32 percent), followed by cropland (58.73 per cent) and scrubland (57.53 per cent). While the lowest CV was recorded for forest (28.88 per cent) which indicates the lesser risk of poor vegetation water content thus leading to constant vegetation greenness within the forest ecosystem. Overall, the result shows that the CV enhances small variation in forest owing to lower NDWI value deviation, but suppresses the much greater variation in plantation because of the overall higher deviation of NDWI values. This variation due to change in overall NDWI values can be related to works carried out by Fang *et al.* (2001) and Barbosa *et al.* (2006) where the presence or absence of dry periods or wet periods were suggested as the reason for the inter-seasonal variations in land covers.

During the Rabi season (Table II), the NDWImax value is recorded highest for swamp forest (0.59), which is related to high water content capacity of mangroves located in the coastal regions along the delta, while the NDWImin is noticed for the scrubland (-0.07) and plantation land (-0.07). The mean NDWI value is recorded highest for swamp forest (0.31) followed by forest (0.28) and scrub forest (0.23). The higher NDWI in swamp forest and forest might be due to the presence of good water holding capacity shown by perennial trees (Traore *et al.,* 2014). In terms of cropland (Rabi), NDWI varied from -0.07 (NDWImin) to 0.44 (NDWImax). Overall, it is seen that NDWI in cropland during Rabi season is found to be more sensitive to NDWI compared to Kharif season which might be due to vegetation health and biomass development during Rabi season period (Huete *et al.,* 2002).

Table II. Zonal Averaged NDWI of Land Covers in Tamil Nadu during the *Kharif* and *Rabi* season

Kharif Season					
Land Cover	**Minimum**	**Maximum**	**Mean**	**Standard** Deviation	**Coefficient of** Variation
Cropland	-0.14	0.39	0.13	0.08	58.73
Plantation Land	-0.14	0.41	0.15	0.1	66.32
Forest	-0.09	0.44	0.24	0.07	28.88
Scrubland	-0.03	0.40	0.17	0.1	57.53
Swamp Forest	-0.03	0.57	0.20	0.1	50.74
Rabi Season					
Land Cover	**Minimum**	**Maximum**	**Mean**	**Standard** Deviation	**Coefficient of** Variation
Cropland	-0.08	0.44	0.18	0.08	43.02
Plantation Land	-0.07	0.44	0.21	0.07	33.02
Forest	0.05	0.44	0.28	0.04	15.7
Scrubland	-0.07	0.40	0.23	0.07	28.8
Swamp Forest	0.07	0.59	0.31	0.07	22.76

The coefficient of variation (CV) (Table II) is recorded highest for cropland (Rabi) (43.02 per cent), while the lowest CV was recorded for forest (15.7 per cent). The CV values for plantation and swamp forest were found to be 33.02 per cent and 22.76 per cent respectively. While the scrubland shows a CV value of 28.80 per cent. The percentage of the higher coefficient of variation in cropland during Rabi season indicates that the risk of getting poor vegetation development was high for croplands. This might be due to the fact that Rabi season croplands are highly dependent on rainfall received during North East Monsoon (Patel et al., 2001). Overall, higher NDWI deviation is noticed in cropland land, indicating that higher variation is noticed in moisture availability of crops (Tucker *et al.,* 1991). Irrespective of land cover, the CV value was found to be lower for Rabi season when compared to Kharif season which could be the result of wet periods during the growing season or presence of high precipitation in a part icular region (Chen *et al.,* 2006).

CONCLUSION

The potential of MODIS satellite-Terra sensor that provides large-scale monitoring of land surface changes proved to be cost and time effective for gathering information in support of monitoring vegetation biomass and crop-water variations. NDVI due to its simplicity in calculation, easy interpretation and global use can be largely utilized for monitoring vegetation greenness and browning while NDWI response to moisture is instantaneous without any time lag and does not saturate at high biomass levels unlike NDVI that gets saturated at high canopy density due to high sensitivity to canopy chlorophyll changes, combining these indicators can prove to be a robust approach for agricultural drought monitoring.

Based on the study, observations were made which indicated the presence of maximum NDVI from the forest (0.91) and scrubland (0.91) vegetation cover during Kharif season, while in the Rabi season also similar figures were obtained, wherein forest cover (0.90) followed by scrubland (0.88) had maximum NDVI. In both the seasons, the coefficient of variation was found to a minimum for the forest, however, the variation was found to be higher during Kharif season (12.67) than Rabi season (8.47). In case of NDWI response, the maximum NDWI was observed for swamp forest (0.57) while the minimum NDVI was also observed for swamp forest (-0.03) along with scrubland (-0.03) during Kharif season. While during the Rabi season, maximum NDWI was notice in swamp forest (0.59) and the minimum in scrubland and plantation (-0.07). The Coefficient of Variation was recorded highest for plantation

(66.32 per cent) during *Kharif* season and during *Rabi* season it was noticed highest for cropland (43.02 per cent).

The occurrence of dense vegetation conditions in the land covers of Tamil Nadu is attributed to the presence of crop diversification and possible changes in habitat characteristics along with the presence of perennial vegetation within the ecosystem, while little variation in the croplands during Kharif season and Rabi season may attribute to the abrupt climatic changes that influence the vegetation growth. Based on the comparison of both the indices for vegetation change detection, NDWI showed greater inter-seasonal variations due to presence or absence of dry period or wet periods during the crop growing season in the state of Tamil Nadu.

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REFERENCES

Barbosa, H. A., A. R. Huete and W. E. Baethgen. 2006. A 20-year study of NDVI variability over the Northeast Region of Brazil.*Journal of Arid Environments,* **67(2)**: 288-307.

Chen, Y. N., H. Zilliacus, W. H. Li, H. F. Zhang and Y. P. Chen. 2006. Ground-water level affects plant species diversity along the lower reaches of the Tarim river, Western China. *Journal of Arid Environments,* **66(2)**: 231-246.

Fang, J., S. Piao, Z. Tang, C. Peng and W. Ji. 2001. Interannual variability in net primary production and precipitation. Science, **293(5536):** 1723-1723.

Gilabert, M. A., J. González-Piqueras, F. J. García-Haro and J. Meliá. 2002. A generalized soil-adjusted vegetation index. *Remote Sensing of Environment,* **82(2-3)**: 303-310.

Gumma, M. K., P. S. Thenkabail, A. Maunahan, S. Islam and A. Nelson. 2014.

Mapping seasonal rice cropland extent and area in the high cropping intensity environment of Bangladesh using MODIS 500 m data for the year 2010. *International Journal of Photogrammetry and Remote Sensing,* **91:** 98-113.

Huete, A., K. Didan, T. Miura, E. P. Rodriguez, X. Gao and L. G. Ferreira. 2002.Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote sensing of environment*, **83(1-2)**: 195-213.

Hussein, S. O., F. Kovács and Z. Tobak. 2017. Spatiotemporal assessment of vegetation indices and land cover for Erbil city and its surrounding using MODIS imageries. *Journal of Environmental Geography*, **10(1-2)**: 31-39.

Lambin, E. F., B. L. Turner, H. J. Geist, S. B. Agbola, A. Angelsen, J. W. Bruce and P. George. (2001). The causes of land-use and land-cover change: moving beyond the myths. *Global environmental change,* **11(4)**: 261-269.

Mora, F. and O. Arriagada. 2016. A classification proposal for coefficients of variation in Eucalyptus experiments involving survival, growth and wood quality variables. *Bragantia,* **75(3):** 263-267.

Nemani, R., H. Hashimoto, P. Votava, F. Melton, W. Wang, A. Michaelis, L. Mutch, C. Milesi, S. Hiattand M. White. 2009. Monitoring and forecasting ecosystem dynamics using the Terrestrial Observation and Prediction System (TOPS). *Remote Sensing of Environment*, **113(7)**: 1497-1509.

Richter, K., P. Rischbeck, J. Eitzinger, W. Schneider, F. Suppan and P. Weihs. 2008. Plant growth monitoring and potential drought risk assessment by means of Earth observation data. *International Journal of Remote Sensing*, **29(17-18)**: 4943-4960.

Schmidt, H. and A. Karnieli. 2000. Remote sensing of the seasonal variability of vegetation in a semi-arid environment. *Journal of Arid Environments,* **45(1)**: 43–59.

Singh, R. P., S. Roy and F. Kogan. 2003. Vegetation and temperature condition indices from NOAA AVHRR data for drought monitoring over India. *International Journal of Remote Sensing*, **24(22)**: 4393-4402.

Townshend, J., Justice, C., Li, W., Gurney, C., & McManus, J. (1991). Global land cover classification by remote sensing: present capabilities and future possibilities. *Remote Sensing of Environment,* **35(2-3)**, 243-255.

Traore, S. B., A. Ali, S. H. Tinni, M. Samake, I. Garba, I. Maigari and P. O. Dieye.2014. AGRHYMET: A drought monitoring and capacity building center in the West Africa Region. *Weather and Climate Extremes,* **3:** 22-30.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment,* **8(2)**: 127-150.

Tucker, C. J., H. E. Dregne and W. W. Newcomb. 1991. Expansion and contraction of the Sahara Desert from 1980 to 1990. *Science*, **253(5017)**: 299-300.