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RESEARCH ARTICLE Indian Journal of Agricultural Research

Spatio-temporal Assessment of Land Surface Temperature, Vegetation and Crop Water Stress for Sustainable Land Management in Upper Brahmaputra Valley, Assam

Arunima Nandy[1], Avinash Kumar[1]

10.18805/IJARe.A-6415

ABSTRACT

Background: Land surface temperature (LST) and vegetation play a very significant role in influencing soil moisture and its interaction with the crop. Crop Water Stress Index (CWSI) is one of the most applicable indices to measure the level of water stress to crops that can be quantified using satellite imagery. The upper Brahmaputra river valley of Assam is a rapidly growing region experiencing extensive urban expansion, which necessitates the assessment of changes in spatio-temporal LST and vegetation dynamics for sustainable land management.

Methods: MODIS images were applied in this study to assess spatio-temporal LST, vegetation and Crop Water Stress (CWS). Normalized Difference Vegetation Index (NDVI) was adopted to assess the spatio-temporal vegetation dynamics. A correlation study was conducted to understand the relationship between LST, NDVI and CWSI.

Result: It was observed that there was a strong negative correlation between LST and NDVI, whereas a strong positive correlation was found between LST and CWSI. Hotspot areas characterized by high temperature, low vegetation and high crop water stress were delineated in the ArcGIS platform. Between 2001 and 2021, all LST zones showed an increase in both maximum and minimum temperatures. Contour tilling, mulching and shade nets may effectively enhance soil moisture retention, fertility and microclimatic conditions in these hotspot areas.

Key words: Crop Water Stress Index, Land management, Land Surface Temperature, Normalized Difference Vegetation Index, Remote sensing.

INTRODUCTION

LST is a significant geophysico-climatic parameter related to surface energy and water balance of Earth's lithosphere and atmosphere system (Li *et al.,* 2023). It is an important factor in research of soil moisture (Wang *et al.,* 2022) and urban heat island (Tsou *et al.,* 2017). High resolution (Ingle *et al.,* 2025) and extensive spatio-temporal coverage of remotely sensed imageries (Buraka *et al.,* 2022; Li *et al.,* 2023; Binh *et al.,* 2025) provides advanced, reliable information regarding LST, suppressing the traditional field-based surface temperature measurements (Tomlinson *et al.,* 2011). Among all the wavelengths of the electromagnetic spectrum, thermal imagery is capable of providing LST information over large (Trigo *et al.,* 2008) and remote areas (Gök *et al.,* 2024). Satellites with thermal infrared sensors like ASTER (Schmugge *et al.,* 2002) Landsat (Sekertekin and Bonafoni, 2020) and MODIS (Yoo *et al.,* 2020) enable frequent monitoring of temporal changes of LST. This capability is significant for applications in meteorology and climate research and in understanding of LST fluctuations and their environmental implications (Tomlinson *et al.,* 2011). Moreover, LST serves as a fundamental parameter in contemporary agricultural practices, facilitating the assessment of Crop Water Stress (CWS) (Raoufi and Beighley, 2017) and soil moisture (Pashova and Mihaylova, 2025) through the application of remote sensing. CWS is an important indicator in understanding the environmental interaction of a crop (Idso *et al.,* 1981); that evaluates water deficit conditions by utilizing leaf-scale measurements and crop temperature analysis (Zhou *et al.,* 2021). Conventional approaches to measure CWS can be complicated by soil heterogeneity and may not provide a direct indication of the crop's water status (Pradawet *et al.,* 2023). In contrast, recent advance remote sensing techniques, such as spectral vegetation indices, infrared and thermal remote sensing, have gained popularity due to their reliability and efficiency in data collection (Mwinuka *et al.,* 2021).

Upper Brahmaputra River valley of Assam has unique climatic and hydrological conditions. The soil moisture and

[1]Department of Agricultural Engineering, Assam University, Silchar-788 011, Assam, India.

Corresponding Author: Avinash Kumar, Department of Agricultural Engineering, Assam University, Silchar-788 011, Assam, India. Email: avinashiitkgp86@gmail.com
ORCIDs: 0000-0002-2373-1979; 0000-0002-0254-3186

How to cite this article: Nandy, A. and Kumar, A. (2025). Spatio-temporal Assessment of Land Surface Temperature, Vegetation and Crop Water Stress for Sustainable Land Management in Upper Brahmaputra Valley, Assam. *Indian Journal of Agricultural Research*. 1-8. doi: 10.18805/IJARe.A-6415.

Submitted: 10-05-2025 **Accepted:** 14-08-2025 **Online:** 01-10-2025

the associated crops is greatly controlled by the seasonal rainfall patterns, complex topography (Saikia *et al.,* 2019) and distinct floodplain ecosystem of the region. The assessment of CWS in relation to soil and water conservation practices in this valley remains unexplored, which limits effective agricultural management in the region. Addressing these gaps is crucial for improving water-use efficiency and agricultural practices in this region.

This study estimates spatio-temporal changes of LST, vegetation and CWS of the upper Brahmaputra River valley of Assam using high temporal resolution MODIS LST and NDVI data from 2001 to 2021. Crop Water Stress Index (CWSI) was adopted in this study to quantify the soil moisture. The correlation coefficient was studied between LST, NDVI and CWSI to understand the relationship between these three factors. On the basis of maps of LST, NDVI and CWSI, hotspot areas having high temperatures, low vegetation and high crop water stress were identified in the study area. Furthermore, some sustainable land management strategies were proposed for these hotspot areas in the valley.

MATERIALS AND METHODS

Study area

The upper Brahmaputra River valley of Assam includes the districts of Tinsukia, Dhemaji, Dibrugarh, Lakhimpur, Sibsagar, Jorhat and Golaghat (Fig 1). Among all the districts, Tinsukia and Golaghat are falling under high flood vulnerable index (0.64-0.75) and Dhemaji, Dibrugarh, Jorhat, Lakhimpur and Sivsagar are falling under relatively moderate vulnerable index (0.532-0.639) (World Bank, 2024). This research work was carried out in the Department of Agricultural Engineering, Assam University, Silchar, Assam, during the period 2024-2025.

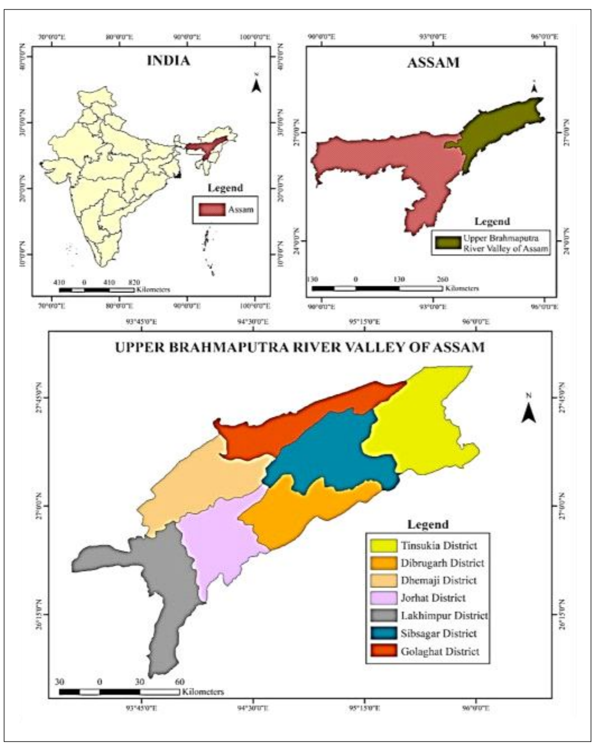

Fig 1: Map of the study area.

Data collection

MODIS Terra version 6.1 data, MOD11A2 and MOD13A2 were used in this study for LST and NDVI analysis respectively. MOD11A22001113, MOD11A22021113, MOD13A22001113 and MOD13A22021113 were used to analyze spatio-temporal LST and vegetation change respectively from 2001 to 2021.

Measurement of LST

LST refers to the temperature emitted by the surface (Rajeshwari and Mani, 2014). LST have significant impact on various phenomena including geological and geothermal studies (Sekertekin and Arslan, 2019), drought (Nugraha *et al.,* 2023) and forest fire monitoring (Maffei *et al.,* 2018). Remote sensing provides LST data using thermal infrared sensors (Sekertekin and Bonafoni, 2020). The MODIS Terra MOD11A2 product delivers LST data using thermal infrared radiance measurements utilizing the Generalized Split-Window Algorithm (GSWA) to effectively correct for atmospheric influences and variations in surface emissivity.

Radiance measurement

MODIS effectively captures radiance within the thermal infrared spectrum, especially in bands 31 (10.78-11.28 μm) and 32 (11.77-12.27 μm) (Wan and Dozier, 1996).

Brightness temperature conversion

The at-sensor radiance is transformed into brightness temperatures (T1 and T2) utilizing the Planck function (Wan, 2019).

Atmospheric correction

Atmospheric parameters, including water vapour content, are derived from ancillary data sources such as the NCEP/DOE reanalysis. These parameters are employed to correct for the atmospheric influence on radiance measurements (Wan, 2014).

Generalized split-window algorithm

LST is calculated utilizing a relationship between brightness temperatures from bands 31 and 32. The formula for LST is expressed as Equation 1:

$$LST = T_1 + a(T_1 - T_2) + b(T_1 - T_2)^2 + c + dW + eW^2 \quad ....(1)$$

Where,

T_1 = Brightness temperature in band 31.

T_2 = Brightness temperature in band 32.

W = Total atmospheric water vapor content.

a, b, c, d, e are empirical coefficients that are determined through radiative transfer modelling. This formulation provides a systematic approach to evaluate

LST considering temperature and atmospheric moisture parameters (Wan and Dozier, 1996).

Surface emissivity adjustment

Surface emissivity values are obtained from ancillary MODIS products or approximated based on land cover classifications. Emissivity corrections are implemented to account for the specific radiative characteristics of the surface (Wan *et al.,* 2004).

Temporal and quality filtering

The MOD11A2 product offers an 8-day composite by selecting the highest-quality pixels from daily LST observations. This methodology effectively minimizes the impact of cloud cover and atmospheric interference (Wan, 2019).

Vegetation index

Dense vegetated areas typically characterize lower LST as a result of the shading effect and evapotranspiration, both of which contribute to cooling the surface specifically in urban environments (Kim *et al.,* 2022). Moreover, soil moisture is greatly dependent on the distribution of vegetation (Schenk and Jackson, 2002). NDVI is a very promising index to understand the health and distribution of vegetation. This index is determined using the variations in near-infrared and red reflectance of vegetation. It ranges from -1 to +1 (Rouse *et al.,* 1973). Spatio-temporal NDVI analysis was performed in this study using the following formula as presented in Equation 2.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \qquad ....(2)$$

Crop Water Stress Index (CWSI)

Prolonged high LST can lead to moisture loss due to an increase in the evaporation rate from the soil (Pablos *et al.,* 2014), raises plant transpiration rates (Cammalleri and Vogt, 2015) and also can reduce soil's moisture retention capacity over time (Idso *et al.,* 1981). This water deficit condition of the soil can be determined through CWS (Ahmad *et al.,* 2021). CWSI is one of the most adopted indices to assess the stress level at the canopy and leaf scales based on the difference in air temperature, canopy temperature and vapour pressure deficit. CWSI was calculated in this study using Equation 3 (Idso *et al.,* 1981):

$$CWSI = \frac{(T_c - T_a) - LL}{UL - LL} \qquad ....(3)$$

Where,

Tc = Canopy temperature.

Ta = Air temperature.

LL and UL = Lower and upper limits of water stress, respectively.

The framework of the methodology of this study is represented in Fig 2.

RESULTS AND DISCUSSION

Spatio-temporal changes of LST

This study examined the LST from 2001 to 2021 (Fig 3) using MODIS images. This spatio-temporal analysis indicated a concerning rise in very high temperatures, which increased by 7.16°C over two decades. In 2001, zones of very high temperatures were predominantly found in the southern regions of the Golaghat district and parts of Lakhimpur district. High-temperature zones were also identified in the northern and north-western sectors of Lakhimpur and the western and north-western portions of Dhemaji district. By 2021, however, the thermal landscape had undergone substantial changes. The very high temperature zone had expanded further into the southern segment of the valley and clusters of high temperatures were also detected in the northern, central and eastern regions.

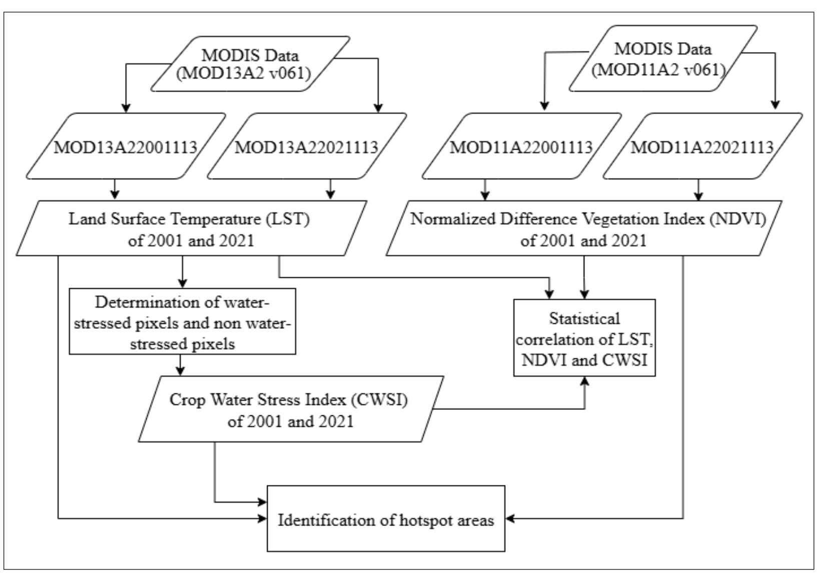

Fig 2: Framework of the research methodology.

The percentile spatio-temporal changes of maximum and minimum temperatures of the valley were analyzed in Table 1. It was found that the maximum and minimum very high temperatures increased by 19.38% and 9.03% respectively, in two decades. These may result from increasing population (as according to the last census of India, 2011, the decadal growth of population of all the districts of the study area was 96.08% from 2001 to 2011), gradual expansion of concrete surface, global warming and decrease of vegetation.

Spatio-temporal changes of LST were assessed based on changes in maximum and minimum recorded temperature of each LST zone.

Changes in vegetation

The presence of dense vegetation plays a crucial role in significantly reducing the temperature of a region over long term. However, climatic changes, particularly fluctuations in temperature, can extremely impact the health and life of plant. In this study, NDVI was applied to evaluate the changes in vegetation in response to varying temperature conditions. Observations from the NDVI maps of 2001 and 2021 (Fig 4) indicated that the alterations in the region's temperature were reflected in the vigor and distribution of the vegetation. As temperatures shifted, the resilience and expansion of plant life were directly affected, creating a

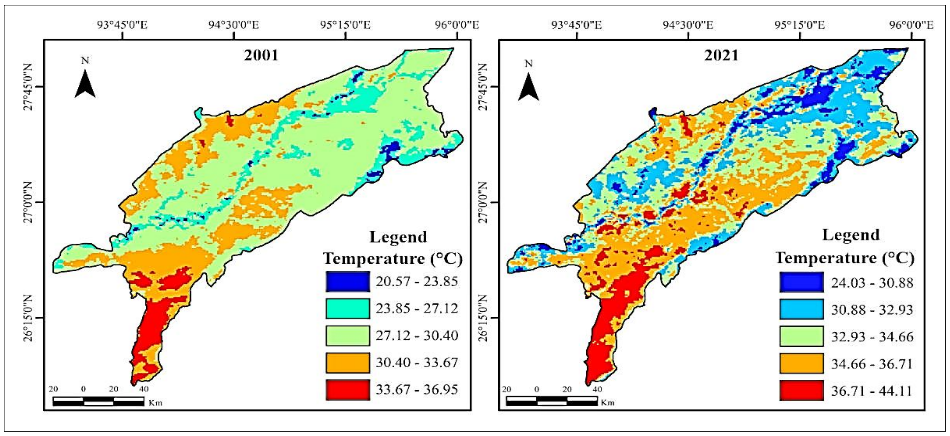

Fig 3: Land surface temperature maps of the valley of 2001 and 2021.

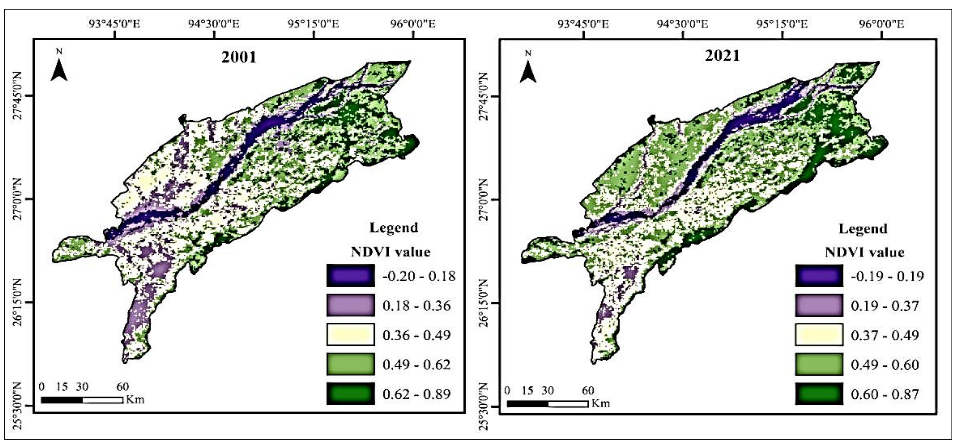

Fig 4: NDVI maps of the upper Brahmaputra river valley of Assam of 2001 and 2021.

Table 1: Spatio-temporal changes in LST from 2001 to 2021.

Zones of LST	Maximum		Minimum		Percentage of change (2001-2021)	
	2001	2021	2001	2021	Max	Min
Very low	23.85	30.88	20.57	24.03	29.48	16.82
Low	27.12	32.93	23.85	30.88	21.42	29.48
Moderate	30.40	34.66	27.12	32.93	14.01	21.42
High	33.67	36.71	30.40	34.66	9.03	14.01
Very high	36.95	44.11	33.67	36.71	19.38	9.03

dynamic relationship between climate and ecological health.

The mean values of each NDVI class to analyse the changes in NDVI across all classes from 2001 to 2021 is presented in Fig 5. It was revealed that there was a negative change in the high and very high NDVI classes from 2001 to 2021.

Variations in crop water stress

Soil moisture is intrinsically linked to surface temperature. Areas characterized by optimal soil moisture levels experience reduced crop water stress. In contrast, soils with insufficient moisture contribute to heightened crop water stress, subsequently diminishing agricultural productivity and increasing dependency on irrigation systems. Spatio-temporal CWSI was applied in this study (Fig 6), revealing that the regions subjected to high temperatures exhibited increased water stress. In contrast, areas with significant water bodies and dense vegetation demonstrated less CWS.

Interrelationship between LST, NDVI and crop water stress

The relationship among two or more variables can be comprehensively understood by applying statistical correlation techniques. Pearson's correlation coefficient (r) was utilized to explore the relationship between LST, NDVI and CWSI. The value of the Pearson correlation coefficient can range from +1 to -1. A value approaching +1 signifies a strong positive correlation, 0 denotes no significant relationship, while -1 indicates a strong negative correlation.

The correlation coefficient (r) between LST and NDVI of 2001 and 2021 (Fig 7) was calculated as -0.87 and -0.89, respectively. This highly negative value suggested a strong inverse relationship between surface temperature and vegetation health, meaning that as surface temperatures rise, the vegetation index tends to decline. On the other hand, the correlation coefficient (r) between LST and CWSI of 2001 and 2021 (Fig 7) was found to be 0.99 for both years, revealing a very strong positive correlation. This indicated that increases in LST are closely linked to increases in the CWSI, suggesting that higher temperatures are associated with greater water stress in soil and directly with associated crops.

Identification of hot spots

The areas having high temperature with low vegetation and high-water stress were identified as a hotspot. The

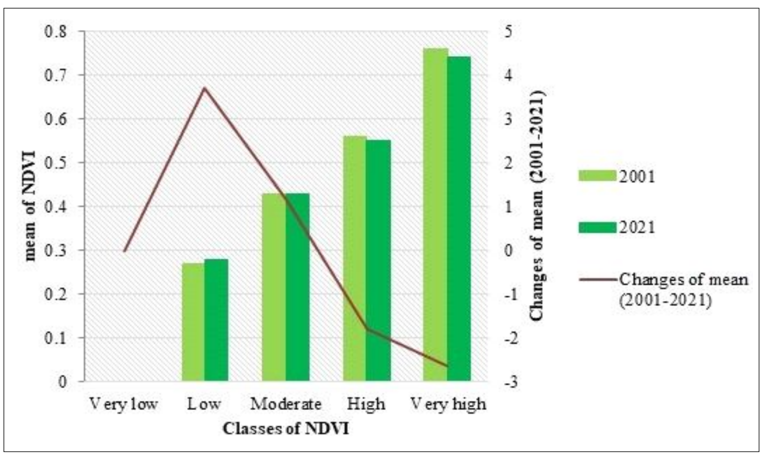

Fig 5: Changes in NDVI from 2001 to 2021.

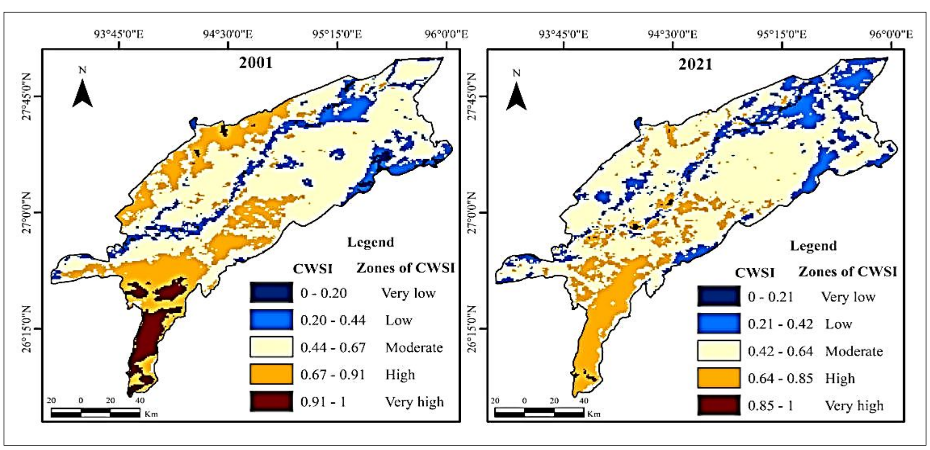

Fig 6: Crop water stress index maps of the study area of 2001 and 2021.

LST maps of the valley easily portrayed the areas that are experiencing high temperatures. NDVI maps helped to identify areas with low vegetation. Moreover, the areas experiencing high water stress were easily identifiable through maps of CWSI. To delineate the hotspot areas, one condition was applied using the raster calculator in ArcGIS as follows:

Con ((raster layer of ‘LST’ > ‘upper limit of moderate class of LST’) and (raster layer of ‘NDVI’ < ‘upper limit of moderate class of NDVI’) and (raster layer of ‘CWSI’ > ‘upper limit of moderate class of CWSI’), 1, 0).

The resultant raster layer represented two classes. One class (represented as 1) had all the areas that were experiencing high temperature, low vegetation and high water stress conditions. On the other hand, another class consisted of all the areas which were not fulfill the above condition (represented as 0). The hotspot areas were represented in Fig 8 for 2001 and 2021.

Spatio-temporal maps of the hotspots revealed that the total area coverage of hotspots increased by 67.33% from 2001 to 2021.

Proposed strategies for sustainable land management

LST assessment revealed that the valley had experienced an increase in temperature with high zonal variability. This may be because of irregular climate; global warming is unevenly spread over all areas. Regions with low temperature and high vegetation are converting into environmentally sensitive areas due to land-use changes, deforestation and rapid urbanization. These regions are becoming hotspots having high temperature, low vegetation and high water stress. These variations seek zone-specific land management planning and mitigation approaches. Strategies for sustainable land management specifically for agricultural practices in this region need adaptation of soil retention techniques that can minimize the problems associated with high temperature, low vegetation and high

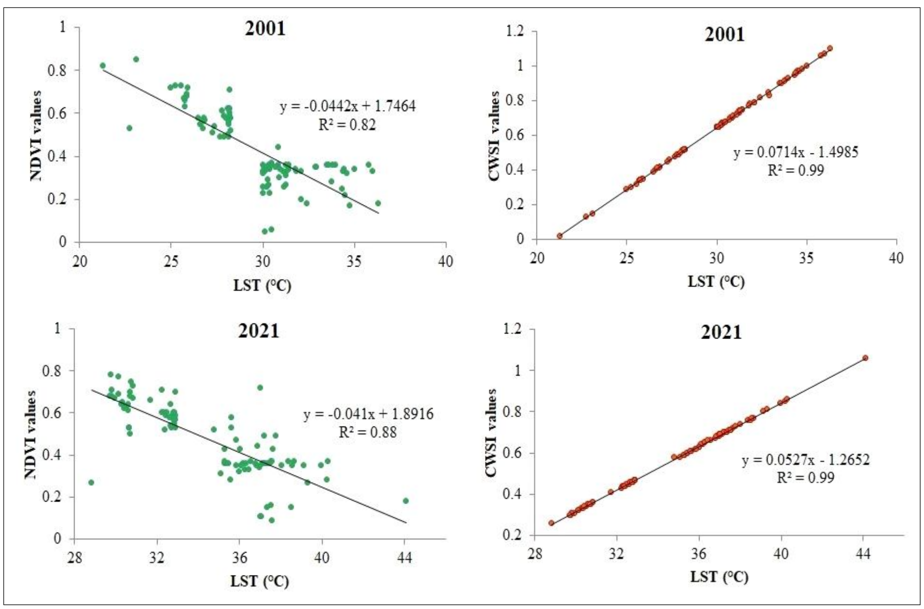

Fig 7: Correlation among LST, NDVI and CWSI for 2001 and 2021.

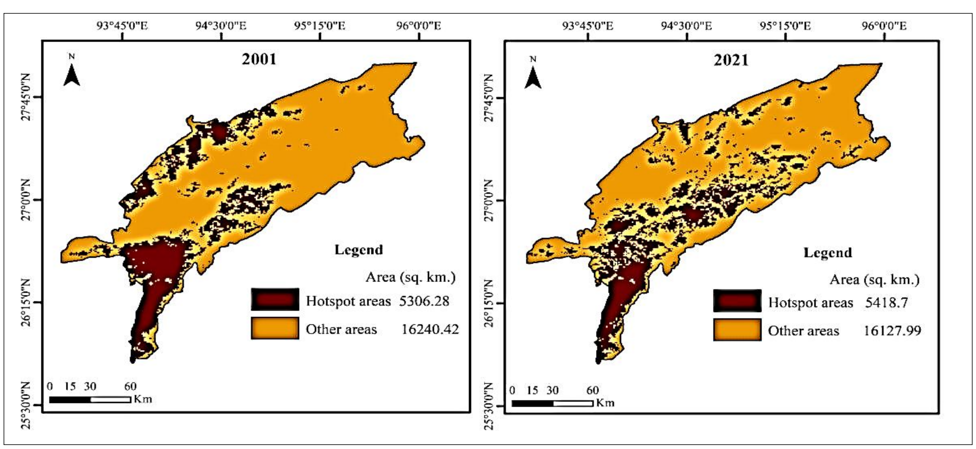

Fig 8: Hot spots of the valley of 2001 and 2021.

CWS. Such management strategies will be beneficial for the hotspot areas, as this is a dominant agrarian region. Some proposed strategies for this region are as follows:

- Cultivation along contours (contour tilling) helps to retain soil moisture by minimizing surface water runoff and providing more infiltration time to the soil for water (He *et al.,* 2017). This technique can be applied in the hotspot areas along long contours to retain soil moisture.
- Mulching technique is another technique that helps to retain organic content and moisture (Kader *et al.,* 2019). This method can be applied to improve the fertility of the hotspot areas in the valley. It can enhance fertility by using a mix of organic and inorganic materials, which helps suppress weeds, reduce evaporation and control soil temperature.
- Shade net is a popular agricultural technique that creates a micro-environment by reducing wind speed and increasing air-moisture. It regulates transpiration and air temperature, offering an economic method for enhancing agro-climates in hotspot areas of the valley.

CONCLUSION

Earth's surface temperature and soil moisture are two interconnected factors that directly influence the health of vegetation and the level of crop water stress. This study found that changes in temperature significantly affect both vegetation and CWS. Specifically, when temperature rises; the vegetation vigor decreases, while CWS increases. Conversely, when temperatures drop, the situation reverses. Statistical correlation analysis of temperature, vegetation and water stress portrayed their interrelationships, which is crucial for developing strategic irrigation management plans, especially during contemporary climate change. Such challenging environmental conditions of the hotspot areas can affect both the sustainability and productivity of the land. The study will be more enriched with the application of high spatial resolution satellite images associated with field data to measure the changes of LST and its impact on soil moisture in the region. Assessment of soil quality and fertility will further enhance the framing of sustainable land management strategies for the region. Afforestation and the development of infrastructure for cool-green environment can be adopted for the environmentally sensitive areas. The proposed land management strategies in this study are expected to be beneficial in retaining the sustainability of the hotspot areas and may increase the agricultural prospects in the valley.

ACKNOWLEDGEMENT

The authors are grateful to the NASA LP DAAC; USGS Earth Explorer; SOI, Guwahati; IMD and NBSS and LUP, Jorhat, Assam, for providing data.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare no conflict of interest.

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