

## RESEARCH ARTICLE

# A composite method to identify desertification 'hotspots' and 'brightspots'

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**Abstract**

Desertification has become one of the greatest environmental concerns of our planet. Implementation of the action plans for arresting land degradation and for employing rehabilitation measures over a large spatial scale is not feasible due to the amount of time, effort, and cost involved. However, if the 'hotspots', the 'brightspots', and the 'potential areas' are identified, the task would be relatively easy. In this paper, a method is proposed to identify the pieces of degraded land with varying severity levels (in terms of 'hotspots', 'brightspots', and 'potential areas'), using Bowen ratio, land surface temperature (LST),  $R_a$ , and Normalized Difference Vegetation Index (NDVI). Although the zone falls in the semiarid class, the microclimate analysis of the study area revealed high aridity. The combined analysis of LST,  $R_a$ , and NDVI helped in identifying the areas susceptible to land degradation (particularly, salinization and water erosion). Analysis of the vegetation type and condition showed their variable roles towards the protection of soil from erosion, drought, and fire. Using these analyses together with the ecosystemic approach of Bowen ratio, 'hotspots', 'brightspots', and 'potential areas' were identified at the pixel level. For validation, Desertification Status Map was employed. The investigations revealed that around 49% of the study area falls under the category of 'hotspots' (with an error estimate of 13%) and another 49% as 'brightspots'. The findings revealed that instead of targeting the entire area for implementation of the mitigation measures with the same efforts, it would be better to focus on the specific pieces of land ('hotspots') to optimally utilize the available resources.

**KEYWORDS**

'brightspots', 'hotspots', Bowen ratio, desertification, land degradation, land use

## 1 | INTRODUCTION

Dryland ecosystems are very much vulnerable to climate change (Jat, Crauford, Sahrawat, & Wani, 2012) and hence to desertification (Beltagy & Madkour, 2012). Desertification has become one of the most serious environmental problems that the world is facing today. Land degradation and desertification have affected almost 2.6 billion people in more than a hundred countries and has influenced over 33% of the Earth's land surface (www.unccd.int). In India, approximately one-third

of its total geographical area is undergoing the process of land degradation (Ajai, Arya, Dhinwa, Pathan, & Ganesh, 2009). India accounts for 2.4% of the world's geographical area and 0.5% of the world's grazing land, yet it supports 16.7% of the world's population and 18% of the world's cattle population, respectively (Ajai et al., 2009). Thus, there is a tremendous pressure on the country's natural resources and on its environment. Such a huge pressure on land often leads to inappropriate and unsustainable land use practices, degradation of soil, loss of vegetation and water covers, and loss in biological diversity (Bunning,

Mcdonagh, & Rioux, 2011). Mapping, monitoring, assessment, and early warning of desertification are the basic requirements towards the formulation of strategies for preventing, arresting, and combating desertification. A number of methodologies are available for these purposes at global, national, and local scales. Zdruli, Cherlet, and Zucca (2016), Zucca et al. (2012), Sommer et al. (2011), Middleton and Thomas (1997), and Dregne (1986) have reviewed methodologies used for desertification mapping, monitoring, and assessment at global and regional scales. The well-known global approaches include the Global Assessment of Human-Induced Soil Degradation (United Nations Environment Programme, 1992), Land Degradation Assessment in Drylands (Nachtergaele & Licona-Manzur, 2008), Global Assessment of Land Degradation and Improvement (Bai, Olsson, & Schaepman, 2008), United States Natural Resource Conservation Service, Major Land Resource Stress and Condition (Fairbridge, Beinroth, Eswaran, & Reich, 2008), Millennium Ecosystem Assessment (MA, 2005), Land Degradation Assessment and Mapping Method, developed by the French Scientific Committee on Desertification (Brabant, 2010) and World Atlas of Desertification (Cherlet et al., 2018; Middleton & Thomas, 1997). Prince (2016) has carried out a comparative study of the available global level inventories of desertification, such as Global Assessment of Human-Induced Soil Degradation, World Atlas of Desertification, United States Natural Resource Conservation Service, and Land Degradation Assessment in Drylands. The regional approaches include Sahara and Sahel Observatory's Long Term Ecological Monitoring Observatories Network (ROSELT/OSS) in the circum-Saharan zone, UNCCD-Asian Thematic Programme Network (TPN-1) on Desertification Monitoring and Assessment, Assessment of Human-Induced Soil Degradation (ASSOD) for South and Southeast Asia, Land Degradation Index (2d RUE; Del Barrio, Puigdefabregas, Sanjuan, Stellmes, & Ruiz, 2010), and ESA-Mediterranean Desertification and Land use (MEDALUS) for Mediterranean environments (Kosmas, Ferrara, Briasouli, & Imeson, 1999). At the regional level, Xu, Kang, Qiu, Zhuang, and Pan (2009) quantitatively assessed desertification using Landsat data. Enne, Zucca, and Zanolla (2003) have described the in-depth analysis of the methodologies to evaluate the desertification phenomenon. Few of the national initiatives include Australian Collaborative Rangelands Information System for Australia and Indian desertification and land degradation mapping (Ajai et al., 2009, 2007). The Indian initiative has been towards mapping of the desertification status of the country at 1:500,000 scale based on a three-level classification system. Zucca, Lubino, Previtali, and Enne (2005) have demonstrated a method to fight desertification in Morocco and Tunisia. Zucca, Francesca, and Franco (2011) showed the role of fodder shrub plantations in mitigating desertification in Morocco.

The methods available and used for mapping and monitoring of desertification and land degradation at global, regional, and national scales can be broadly classified into two categories: (a) indicator-based methods and (b) mapping of desertification processes/types directly through field survey or using satellite images (Christian, Dhinwa, & Ajai, 2018). The indicators used in desertification mapping and monitoring include vegetation cover, vegetation biomass, net primary production, land use/land cover, rain-use efficiency, vegetation species composition, soil organic carbon stock, and ecosystem services. Many

of these indicators can be derived from satellite images. However, the indicator-based methods are often unable to identify the processes or types of land degradation, and hence, such an inventory may not be useful in making action plans for combating desertification. This is because the combating strategies are different for different land degradation processes (Christian et al., 2018). The second method provides spatial information on the types of land degradation processes (Christian et al., 2018).

Implementation of action plans towards arresting the degradation of land and taking rehabilitation measures, over large areas, is not feasible because of the huge amount of time, effort, and cost involved. However, if the 'hotspots' (areas where swift rehabilitation actions are required as land degradation is severe or the land is extremely vulnerable to desertification; Bunning et al., 2011), the 'brightspots' (areas without significant land degradation or the areas that were formerly degraded/vulnerable but have been rehabilitated because of the effective implementation of the combating measures), and the 'potential areas' (areas that bear the potential of getting degraded under significant changes) of desertification are identified, the task becomes relatively easy as these can be used to prioritize the areas to be taken up for the implementation of combating measures. Therefore, it is important to identify the 'hotspots' and 'brightspots' for preventing further degradation of the land by taking appropriate mitigation/combating measures.

From the environmental perspective, a clear analysis of vegetation and climate profiles of an area are the key factors for understanding, identification, and monitoring of the desertification 'hotspots' and 'brightspots' whereas knowledge of existing land use practices is important for assessing the implication of socio-economic conditions. Generally, fractional vegetation cover, biomass, and leaf area are proportional to precipitation and available soil moisture (Beatley, 1974). A primary driver of desertification is the loss in the vegetative cover that leads to lower precipitation (Charney, Quirk, Chow, & Kornfield, 1977). Thus, a systematic study of any region begins with a detailed analysis of vegetation, climate, and land use pattern in order to find out the drivers of desertification 'hotspots' and 'brightspots'. There are several families of attributes that can be related to the degree of land condition or degradation. One such approach is based on energy ratio or Bowen ratio (García et al., 2008). The approach of energy ratio bears the assumption that Bowen ratio (sensible heat flux/latent heat flux) is expected to increase along the land degradation gradient because land with poor and thin soil affects vegetation density, and this would lead to large sensible heat flux over latent heat flux (Warner, 2004). One more fundamental physical entity that plays a paramount role in the distribution, composition, and productivity of ecosystems through photosynthesis and the water cycle is solar radiation (Piedallu & Gégout, 2007). It is one of the primary variables influencing evapotranspiration and thus soil moisture in semiarid regions (Monteith & Unsworth, 2014). Together with Normalized Difference Vegetation Index (NDVI), it can serve as an effective indicator of desertification.

In view of the above, the approach based on Bowen ratio has been used to identify the desertification 'hotspots' and 'brightspots'. Analysis

of vegetation type and climate helped in the understanding of the driving forces behind the ecosystem's maturity. Additionally, solar radiation is studied along with the NDVI and Land Surface Temperature (LST) profiles. The collective analysis is used to identify desertification-prone areas.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area

Bellary District from the State of Karnataka, India, was selected as the study area (Figure 1). Climatically, the study area falls in the semiarid zone. It spreads around two hills of granite origin (Singh & Ajai, 2008) while covering 8,463 km<sup>2</sup> of surface area. The major land cover, in the study area, comprises agriculture and forests with the considerable portion under wastelands. Bellary District has seven subdivisions, namely, Hadagalli, Hospet, Bellary, Sandrur, Kudligi, Sirguppa, and Hagaribomanahalli. Raichur and Koppal Districts form its northern boundary, Gadag and Haveri the western boundary, Davangere and Chitradurg the south, and Andhra Pradesh the east. Tungabhadra and Hagari are the major rivers of this district (Singh & Ajai, 2008). The district receives an average annual rainfall of 545 mm, mostly between May and September. The mean daily temperature varies within 23°C and 42°C over the year (Singh & Ajai, 2008). The major rock groups in the district are Dharwars, peninsular gneisses, and granites whereas the major soil types are red and black. According to agro-climatic zonation of the Country, the region falls in the southern plateau and hills region (Khanna, 1989). Although, the study was conducted at the pixel level over the entire study area, for validation, a

total of 77 study points were selected through random sampling (Figure 1).

### 2.2 | Materials

#### 2.2.1 | Satellite data

Moderate Resolution Imaging Spectroradiometer (MODIS), on-board Terra satellite, has 36 bands with bands 1–19 and band 26 in the visible and near-infrared range. The remaining bands are in the thermal range from 3 to 15  $\mu$ m. It uses 12 bits for quantization in all bands. MOD11 product for LST and emissivity (8-day composite, 1-km resolution, and sinusoidal grid) and MOD13 product for NDVI (16-day composite, 1-km resolution, and sinusoidal grid) for the time span 2005–2014 were used in this study.

#### 2.2.2 | Ancillary data

The land use map at 1:50,000 scale for the year 2006 was used in this study. It was obtained from the Natural Resources Data Base (NRDB). This map was used to understand the land use pattern of the study area and to analyse the vegetation silhouette with respect to their potentials in causing or aggravating land degradation. Air temperatures for various sites were obtained from the agro-climatological archive of NASA's Global Model and Assimilation Office (GMAO) whereas precipitation was obtained from Global Precipitation Climate Project (GPCP-1DD) satellite-gauge product, which is a global 0.5° × 0.5° daily accumulation based upon the combination of observations from multiple platforms. The in-between spatial data were generated through interpolation. Desertification status map (DSM), prepared by

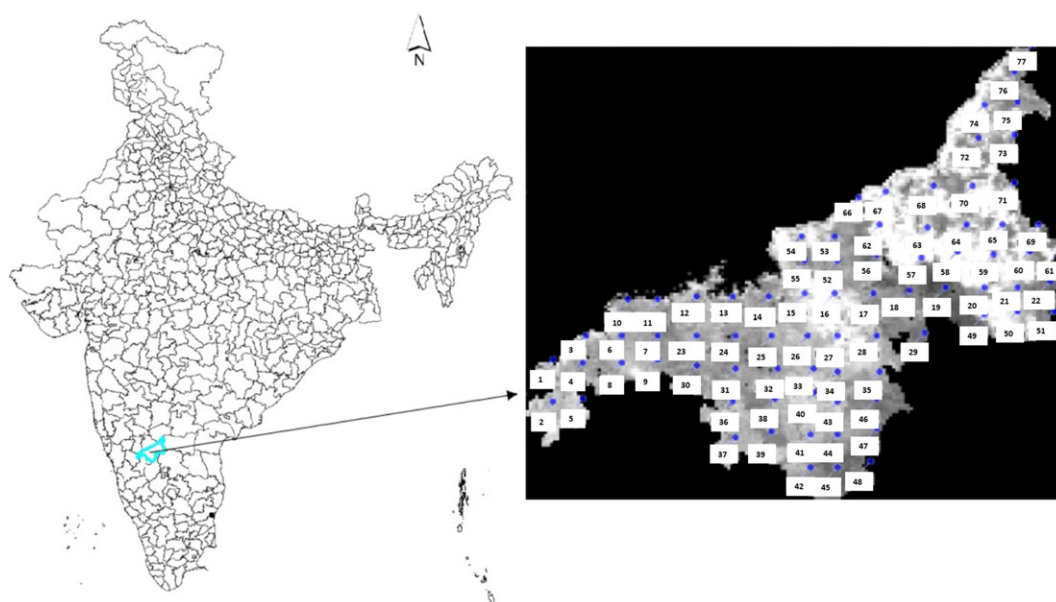


**FIGURE 1** Study area—Bellary District, Karnataka State, India. Also shown are the 77 points for which validation is tabulated [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

the Indian Space Research Organization (ISRO) was used for the validation purpose (Ajai et al., 2009, 2007).

## 2.3 | Method

The main steps involved in the identification of desertification 'hotspots' and 'brightspots' are given below:

1. Microclimate profile analysis
2. Vegetation characteristics analysis
3. Analysis of LST, extraterrestrial solar radiation ( $R_a$ ), and NDVI for three cropping seasons (winter, summer, and monsoon). In India, there are three cropping seasons, *Kharif* (monsoon season), *Rabi* (winter season), and *Zaid* (summer season).
4. Bowen ratio analysis for the three seasons (winter, summer, and monsoon)
5. Collective inferences for the identification of desertification 'hotspots', 'brightspots', and 'potential areas' based on the above-mentioned steps.

The output images generated through the above-mentioned steps of data analysis, were categorized into three levels of desertification: low (count 100), moderate (count 150), and high (count 200) where 100 signifies 'potential area', 150 signifies 'brightspot', and 200 signifies 'hotspot'. The count system was employed for quantification purpose. The final output was computed by integrating all the inputs (climate, vegetation, land use, and Bowen ratio) through geometric mean (Kosmas et al., 1999). The geometric mean was employed so as to ensure that the quantitative range of the parameter(s), upon integration, remains the same. Finally, the output was validated using the available DSM of the study area. The count system was developed based on the field observations, expert knowledge, and the inferences derived from DSM of the study area. From DSM, a number of points pertaining to 'not affected area', low, moderate, and severe degradation were selected. All the intermediate parameters, as well as the values for the final composite output layer, were recorded for these locations. Considering the values obtained for the locations pertaining to low, moderate, and severe degradation (on DSM map and in the

field) and the expert knowledge, the above-mentioned scores were defined.

### 2.3.1 | Microclimate profile analysis

Vegetation adapts to the temperature and precipitation conditions of any region. In other words, it may be said that knowing the type of vegetation, one can predict the climatic conditions of a particular region. In this context, one of the prominent climatic factors is aridity that is crucial to the initiation and progress of desertification. Quantification of aridity is done through an index called aridity index. Numerous aridity indices have been proposed in the literature. In fact, Stadler (1998) gave a review on various aridity indices. The simplest aridity index is based solely on precipitation. UNESCO's aridity index is defined using precipitation and evapotranspiration (UNESCO, 1979). In this study, we have used Bagnouls–Gaussen bioclimatic aridity index (BGI) (Bagnouls & Gaussen, 1953), which is neither too simple as was used by Climate Change (2007) nor computationally complex like that of UNESCO's index. It is defined by Equation (1).

$$BGI = \Sigma(2T_i - P_i).k, \quad (1)$$

where  $T_i$  = mean air temperature in degree Celsius for the  $i$ th month,  $P_i$  = total precipitation in the month  $i$  in mm,  $k$  = proportion of months during which  $2T_i - P_i > 0$ . BGI range interpretation is adapted from Kosmas et al. (1999). Consequently, three classes were formed:  $BGI < 75$  (low), between 75 and 100 (moderate), and  $> 100$  (high).

### 2.3.2 | Vegetation characteristics analysis

The nature and state of vegetation are important indicators of land degradation and desertification. For example, vegetative cover plays an important role in preventing soil erosion and in preserving soil organic carbon. Lee and Skogerboe (1985) showed that 40% vegetative cover is a critical limit beyond which erosion accelerates at high slopes. Forest fire is another important cause of desertification because it not only leads to loss of vegetation but also changes the physio-chemical properties of the soil. It may result in the loss of soil

**TABLE 1** Table for vegetation characteristics analysis

| S. No. | % Plant cover | Vegetation as per fire risk                                               | Vegetation as per drought resistance                     | Vegetation as per erosion protection                                                 | Severity class with respect to land degradation |
|--------|---------------|---------------------------------------------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------------|-------------------------------------------------|
| 1      | >40           | Horticulture, fallow land, agricultural crops, and plantation             | Forests, grasslands, and scrubland                       | Mixed/evergreen forests, plantation, coniferous forest, pine forests, and grasslands | Low                                             |
| 2      | 10–40         | Scrubland, grassland, deciduous, evergreen forests, and forest plantation | Degraded forests, cropped area, and horticulture         | Deciduous forests, scrubland, and horticulture                                       | Moderate                                        |
| 3      | <10           | Coniferous forest, pine forest, mixed forests, and scrub forest           | Shifting cultivation, fallow land, and unproductive land | Agricultural crops, fallow land, and unproductive land                               | High                                            |

nutrients and increase in rain water runoff and erosion, which may also affect the flora and fauna extensively. Different plants possess varied fire-related adaptations (e.g., Brandt & Thornes, 1996). Similarly, different plant species possess unique drought resistance mechanisms through leaf shedding at varying thresholds. For example, cultivated areas with rain-fed crops, such as cereals, are very sensitive to erosion because of their shallow rooting depths, in comparison with forests where rooting depths are very large. Considering equal weights for all of these vegetation characteristics, Table 1 (adapted from Kosmas et al., 1999) is used for understanding the vegetation profile of the study area.

### 2.3.3 | LST, extraterrestrial solar radiation ( $R_a$ ), and NDVI study

Earth's energy balance equation comprises of sensible heat flux ( $H$ ), ground heat flux ( $G$ ), and latent heat flux ( $LE$ ). Together, they are related to net radiation as follows:

$$R_n = G + H + LE, \quad (2)$$

where  $R_n$  = net radiation (incoming flux-outgoing flux).

The amount of  $G$  is negligible as compared with the other two terms. So Equation (2) may be rewritten as

$$LE \sim R_n - H. \quad (3)$$

$$\text{Now, } R_n = (R_{sol} + \sigma \epsilon_a T_a^4) - (\epsilon \sigma T^4 + \alpha R_{sol}), \quad (4)$$

where  $\sigma$  = Stefan's constant,  $\epsilon$ ,  $\epsilon_a$  = surface and air emissivity, respectively,  $T$ ,  $T_a$  = LST and temperature of the air, respectively,  $\alpha$  = albedo, and  $R_{sol}$  = solar insolation, a function of daylight hours and extraterrestrial radiation.

Extraterrestrial radiation is the solar radiation at the top of the Earth's atmosphere, which can be computed as follows (FAO, 1998):

$$R_a = (24 \times 60/\pi)(0.082) \cdot dr [(\omega_s) \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \sin \omega_s], \quad (5)$$

where  $dr$  = inverse relative Earth-sun distance;  $\omega_s$  = sunset hour angle,  $\varphi$  = latitude, and  $\delta$  = solar declination.

$$dr = 1 + 0.033 \cos(2\pi J/365), \quad (6)$$

where  $J$  = Julian day.

$$\omega_s = \arccos[-\tan(\varphi) \tan(\delta)], \quad (7)$$

$$\delta = 0.409 \sin[(2\pi J/365) - 1.39]. \quad (8)$$

When  $R_a$  is large,  $R_{sol}$  will be large and, thus, higher will be the rate of evaporation (Burgess, 2009). In order to minimize moisture loss due to evapotranspiration in water deficit conditions, plants shed their leaves. Hence, persistently high  $R_a$  can give an indication of the stressed ecosystem condition. The effect may be observed from NDVI images. NDVI combines reflectance measurements that are sensitive to the composite effect of foliage chlorophyll concentration, canopy leaf

area, foliage clumping, and canopy architecture. Hence, NDVI is indicative of vegetation vigour. LST may also be used for such studies because it is required for a variety of climatic, hydrological, ecological, and biogeochemical studies (Wan & Li, 1997). It may, therefore, serve as an indicator of the underlying ecosystem's activity, thereby signifying desertification conditions (Sivakumar, 2007).

### 2.3.4 | Bowen ratio analysis for three seasons (winter, summer, and monsoon)

The ratio of sensible heat flux ( $H$ ) to latent heat flux ( $LE$ ) in energy terms is the Bowen ratio ( $H/LE$ ) (Equation (9)). It is expected to increase along the land degradation gradient.

$$\beta = Y(T_s - T_a)/(e_s - e_a), \quad (9)$$

where  $\beta$  = Bowen ratio,  $Y$  = psychrometric constant,  $T_s$  = LST,  $T_a$  = air temperature,  $e_s$  = saturated vapour pressure at LST, and  $e_a$  = saturated vapour pressure at air temperature.

The psychrometric constant can be obtained as follows:

$$Y = 0.665 \times 10^{-3} P, \quad (10)$$

where  $P$  = atmospheric pressure (kPa).

$e_s$  or  $e_a$  may be computed through the following method:

$$e = 0.6108 \exp[(17.27 T)/(T + 237.3)], \quad (11)$$

where  $e$  is  $e_s$  or  $e_a$  and  $T$  is  $T_s$  or  $T_a$ .

However, due to the constraints posed by remote sensing data, Roeder and Hill (2009) suggested sensible heat fraction ( $H/R_n$ ) as a land degradation index equivalent but more operational than  $H/LE$ . A further simplification to reduce the intermediate errors is by computing the ratio NDVI/LST. Here, LST and vegetation density may be taken as surrogates for  $LE$  and  $H$ , respectively. This approach has been used for soil moisture assessment (Sandholt, Rasmussen, & Andersen, 2002) and for the identification of vegetation and land use types (Lambin & Ehrlich, 1996) but could be easily adapted to land degradation assessment (García et al., 2008).

### 2.3.5 | Collective inference for desertification 'hotspots', 'brightspots', and 'potential areas'

From each of the previously mentioned methods, the individual results were categorized into three parts: low (Score 100), moderate (Score 150), and high (Score 200) severity with respect to desertification. The final output was generated by taking the geometric mean of the individual results and was again classified into three levels of severity. The results were validated using the available DSM (Ajai et al., 2007).

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Microclimate profile analysis

Although climate does not change drastically in any region, however, topographic variations impact the microclimate. Average air temperature and precipitation profiles (Figure 2) were observed for three seasons for the period 2005–2014. Aridity index (BGI) was also computed and is shown for the 77 study points in Figure 2.

In Figure 2, average air temperature variation is shown for three seasons for the 77 study points. Barring a few points, all the study points show a consistent average temperature for the winter months. On the contrary, large variation is observed for the summer and rainy months. It is observed that the study area has variations in the air temperature; however, it does not go beyond the optimum temperature range for photosynthesis to occur. The optimum temperature range for photosynthesis is between 20°C and 35°C because photosynthesis slows down beyond this range due to slowing down of the plant's physiological activities (e.g., leaves drop off, and water absorption is reduced at low temperatures). This shows that the present temperature range favours the growth of natural vegetation. Looking at the precipitation distribution (Figure 2), it may be observed that the study region witnessed good rainfall in the months of September and May. Sufficient rainfall creates a favourable environment for the growth of natural vegetation. Appropriate rainfall also implies the prevalence of rain-fed agriculture in this area. However, looking at the values of the aridity index, it is clear that the study locations fall under different aridity conditions. The short-term temperature and precipitation profiles appear to be supportive of the growth of native vegetation/local species. But, according to the aridity profile, which

includes long-term datasets for temperature and precipitation, the ecosystem appears to be weak from the point of view of sustenance. Unsustainable practices of land use might exacerbate desertification.

#### 3.2 | Vegetation profile analysis

Land cover data were analysed with respect to the potential of various land cover types towards (a) safeguarding land from erosion, (b) management of forest fire, and (c) resistance to drought. The resulting maps towards each of these factors are shown in Figure 3.

From the erosion protection map, it is clear that the current land use exposes the land to increased risk of erosion. With the existing precipitation profile, the land in the study area has a high risk of water erosion. The central part of the study area is mainly dominated by deciduous forests (which shed their leaves during summers); hence, this part of the study area is susceptible to drought. The same is observed in the drought resistance map (Figure 3). In the other parts of the study area, the major land use is agriculture that offers moderate resistance to drought. Agricultural crops have shallow rooting depths. The rooting depths influence the vertical distribution of water within the soil column (Kleidon & Heimann, 1998; Pielke, 2001).

NDVI maps of winter, summer, and monsoon seasons (Figure 3) show low NDVI values for the summer season, including some very low NDVI areas. High temperature and depleting water table are the major causes of low NDVI during the summer. In monsoon season, high NDVI values dominate. During the monsoon season, vegetation cover and high soil moisture prevent soil erosion process. However, as the plant cover is less in summer and winter seasons (study area is predominantly agricultural land), the area is highly susceptible to erosion.

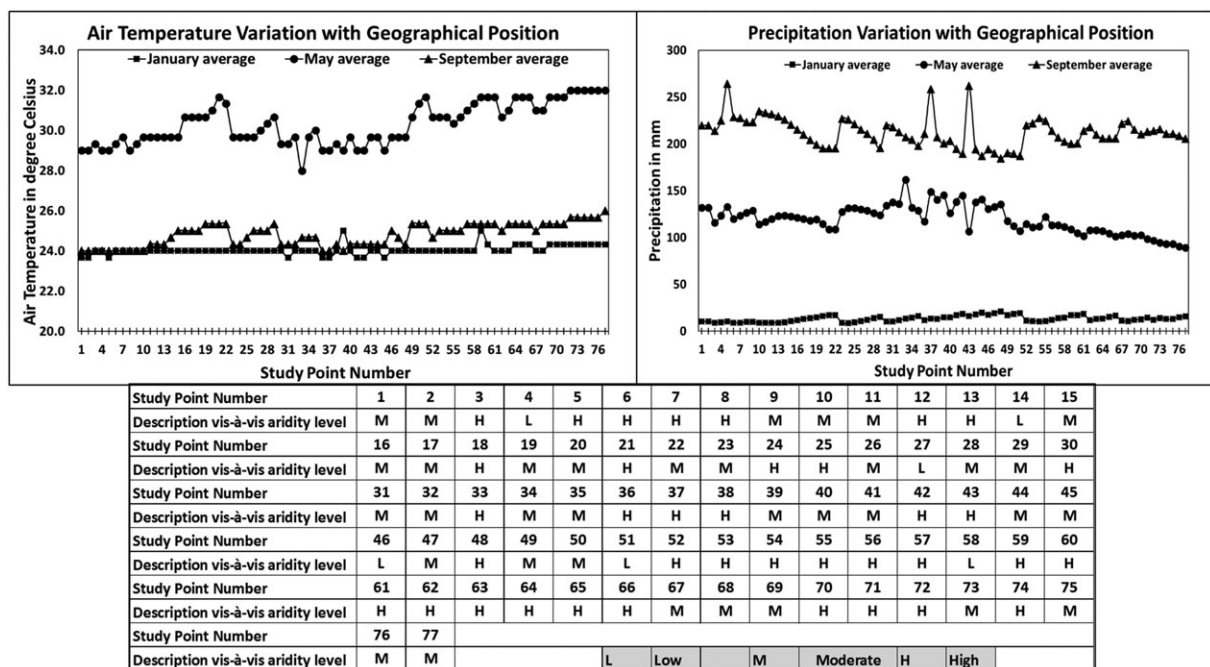


**FIGURE 2** Air temperature, precipitation, and BGI profile for the 77 study points

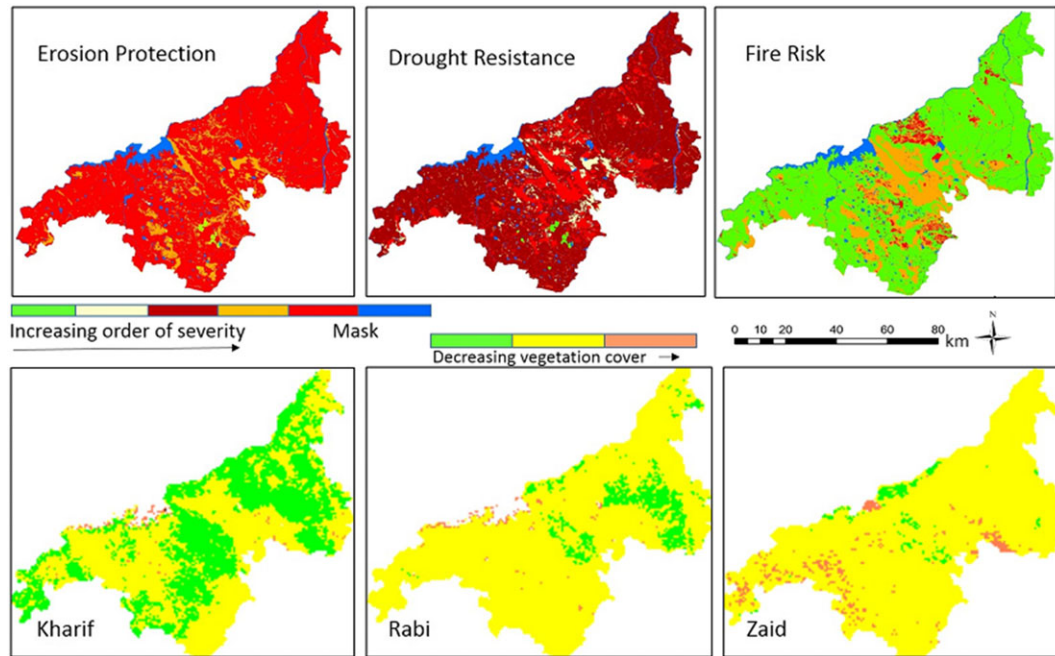


**FIGURE 3** Figures showing vegetation characteristics of the study area for three seasons—winter (*Rabi*), summer (*Zaid*), and rain (*Kharif*), desertification per se [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Because a large part of the study area is under agriculture, fire risk map shows no fire risk zone in most of the areas because agricultural fields are well guarded against all odds. However, the presence of forests makes the region moderately prone to fires especially because of the shedding of leaves. It may be summarized that on an average, the type of vegetation present in the study area offers low protection towards erosion, moderate resistance to drought, and high protection against fire.

### 3.3 | LST, extraterrestrial radiation, and NDVI study for three seasons

One year LST profile for the entire country is shown in Figure 4. Considerable data gaps are observed in the months of May through September. March through May (~315–325 K) experienced high temperatures and good amount of rainfall. This indicates good vegetation growth. For the winter season, LST varies between 300 and 310 K whereas air temperature hardly reaches above 299 K. This indicates the higher contribution of sensible heat flux [ $H = \rho C_p (T_c - T_a)/R_a$ , where,  $\rho$  = air density,  $C_p$  = specific heat of air at constant pressure,  $T_c$  = canopy temperature or LST,  $T_a$  = air temperature, and  $R_a$  = aerodynamic resistance] in maintaining the energy balance equation. Apart from the data gaps observed in the monsoon season, the LST values are found to fall between 305 and 315 K.

The LST image histograms of the three seasons (Figure 4) show a unimodal curve for monsoon season, peaking at 310 K with the highest count, at 315 K for the summer season and at 307 K for the winter season. One can see that LST is consistently high throughout the year for a major part of the study area. High temperatures affect

soil moisture and biological activity and contribute to high evapotranspiration rates (Tereshchenko, Zolotokrylin, Titkova, Brito-Castillo, & Monzon, 2012) that lead to accumulation of salts on the soil surface, for the areas having inherent subsurface soil salinity. Many areas of semiarid regions turn saline/alkaline due to high evapotranspiration rates along with lack of leaching and percolation to deeper horizons. Salinity is a major problem of irrigated land.

When NDVI–LST is studied simultaneously for green vegetation for the three seasons, it is found that majority of the areas have low NDVI values (~0.3) with high LST (~305–310 K) during the winter season. Similarly, for the summer season, a majority of the locations have lower NDVI values (~0.25) with the temperature range of ~303–313 K. High LST with low NDVI is an alarming condition as it indicates ‘potential areas’ of desertification. This situation renders the area into a vulnerable condition where any event of lack of precipitation combined with the anthropogenic effect might lead to a decrease in vegetation cover. This condition might lead to water erosion with the first spell of rain. The land also becomes vulnerable to wind erosion in the event of storms, thereby making the vegetation cover still more difficult to revive. Hence, the study area appears to fall under ‘potential areas’ as regards land degradation and desertification. Unmanaged anthropogenic interference can turn these fragile systems into desertification ‘hotspots’.  $R_a$  values for one complete year for all the 77 study locations are shown in Figure 5.

It is observed that  $R_a$  does not vary much. This causes the plots to overlap (Figure 5). However, seasonal variation exists with a wide range of 29–39 W/m<sup>2</sup>. For the summer season,  $R_a$  remained high at about 38 W/m<sup>2</sup>. LST also remained high during the summer season

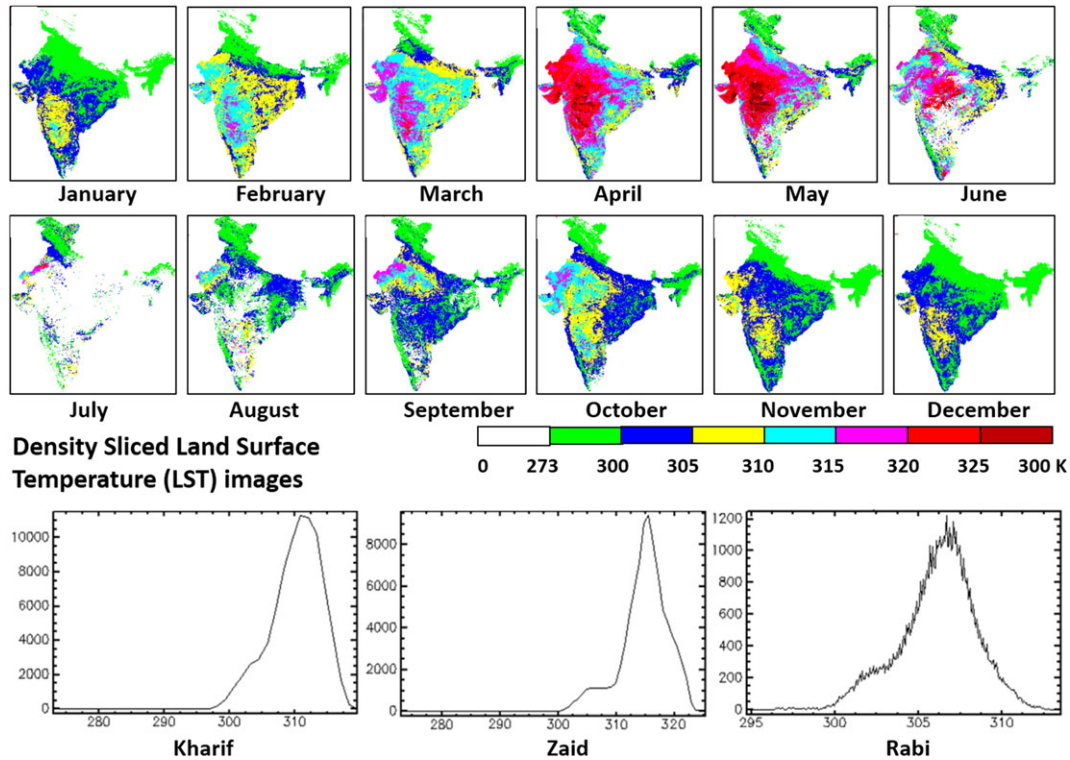


**FIGURE 4** Density sliced LST image for the Country for one complete year [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

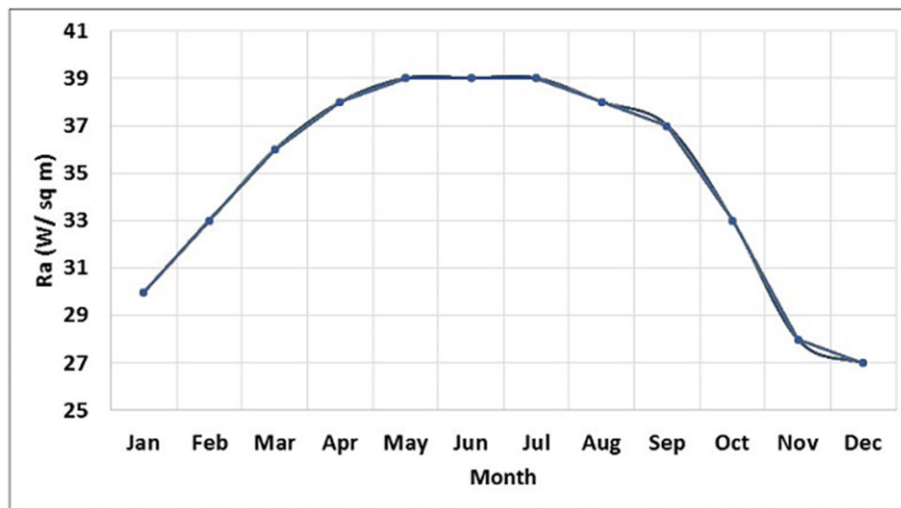


**FIGURE 5** Extraterrestrial radiation profile for the complete year at the 77 study points [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

with a considerable decrease in NDVI. This may be interpreted in the following way: A large value of  $R_a$  represents a large amount of direct radiation that leads to high evapotranspiration rates. At high temperatures along with deficient water supply, plants retain their moisture content by shedding their leaves. This causes a decrease in NDVI value. In such situations, agricultural fields having poor drainage system experience increase in soil salinity. This forms a vicious cycle. Increase in salinity causes a slight reduction in land productivity that leads to low vegetation cover and may affect plant diversity.

### 3.4 | Bowen ratio analysis

#### 3.4.1 | From NDVI-LST ratio

Bowen ratio images generated using NDVI and LST are shown in Figure 6 for monsoon and winter seasons. Because huge data gaps were observed for summer months, the data were not processed. The image was classified based on density slicing method. Because Bowen ratio is the ratio of sensible heat loss to latent heat flux, it tends to be very high

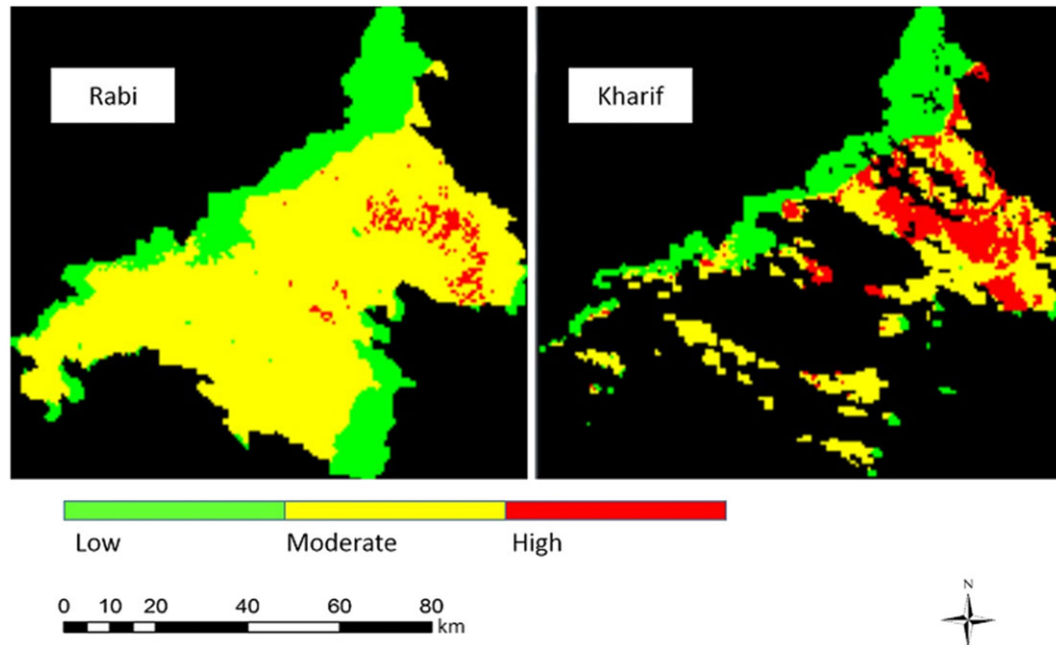


**FIGURE 6** Bowen ratio image for the study area for monsoon (*Kharif*) and winter (*Rabi*) seasons [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

in deserts ( $\sim 10$ ) followed by semiarid regions ( $\sim 2$ – $6$ ), tropical forests ( $\sim 0.4$ – $0.8$ ), and tropical oceans ( $\sim 0.1$ ) (Nobel, 1974).

For the winter season, moderate Bowen ratio is observed for the majority of the areas whereas high Bowen ratio is observed only in a small belt (mainly the agricultural land; Figure 6). This shows that major heat loss from agricultural fields is through sensible heat flux and lesser from evaporative loss (latent heat fluxes), which further suggests poor water condition in these areas. The forest land shows moderate Bowen ratio values, suggesting high evaporative loss and

hence indicate better water conditions. The same is verified from the precipitation profile of the study locations. The belt depicting high Bowen ratio values shows an increase in the area during the transition from winter to monsoon, indicating a rapid increase in sensible heat flux over evaporative loss due to thin vegetation cover. It implies that the area showing high Bowen ratio in winter data is mainly due to poor and thin soil rather than due to vegetation cover. In the figure, the red region of winter data shows land degradation actually present.

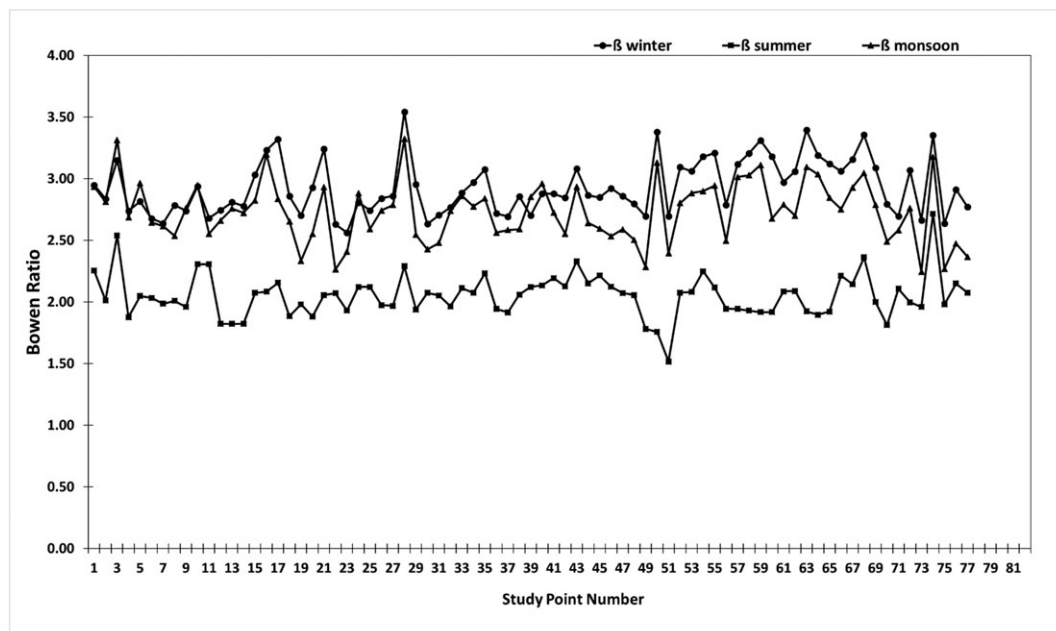


**FIGURE 7** Seasonal trend of the Bowen ratio

**TABLE 2** Table showing a collective inference of desertification status and validation using desertification status map

| S. No. | Climate profile (based on the cumulative effect of variation in average air temperature, precipitation, and aridity) | Vegetation profile (based on erosion protection, drought resistance, fire risk resistance, and plant cover) | Bowen ratio      | Collective inference | Hotspot/bright spot/potential area | Validation              |
|--------|----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|------------------|----------------------|------------------------------------|-------------------------|
| 1      | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | No apparent degradation |
| 2      | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Water erosion           |
| 3      | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | High                 | Hotspot                            | Water erosion           |
| 4      | Low                                                                                                                  | High                                                                                                        | Low to moderate  | Low                  | Potential                          | No apparent degradation |
| 5      | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Vegetal degradation     |
| 6      | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Vegetal degradation     |
| 7      | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Water erosion           |
| 8      | Moderate                                                                                                             | Low                                                                                                         | Moderate         | Moderate             | Brightspot                         | Water erosion           |
| 9      | Moderate                                                                                                             | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | No apparent degradation |
| 10     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Vegetal degradation     |
| 11     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | No apparent degradation |
| 12     | Moderate                                                                                                             | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | No apparent degradation |
| 13     | Moderate                                                                                                             | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | Water erosion           |
| 14     | Low                                                                                                                  | High                                                                                                        | Low to moderate  | Moderate             | Brightspot                         | Water erosion           |
| 15     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Vegetal degradation     |
| 16     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | Moderate             | Brightspot                         | Vegetal degradation     |
| 17     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Vegetal degradation     |
| 18     | Moderate                                                                                                             | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | Vegetal degradation     |
| 19     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | No apparent degradation |
| 20     | Moderate                                                                                                             | High                                                                                                        | Low to moderate  | High                 | Hotspot                            | Salinization            |
| 21     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | Moderate             | Brightspot                         | Urbanization            |
| 22     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Water erosion           |
| 23     | Moderate                                                                                                             | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | No apparent degradation |
| 24     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Water erosion           |
| 25     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Vegetal degradation     |
| 26     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Vegetal degradation     |
| 27     | Low                                                                                                                  | High                                                                                                        | Moderate         | Moderate             | Brightspot                         | No apparent degradation |
| 28     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | Moderate             | Brightspot                         | Urbanization            |
| 29     | Moderate                                                                                                             | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | No apparent degradation |
| 30     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Water erosion           |

(Continues)

TABLE 2 (Continued)

| S. No. | Climate profile (based on the cumulative effect of variation in average air temperature, precipitation, and aridity) | Vegetation profile (based on erosion protection, drought resistance, fire risk resistance, and plant cover) | Bowen ratio      | Collective inference | Hotspot/bright spot/potential area | Validation              |
|--------|----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|------------------|----------------------|------------------------------------|-------------------------|
| 31     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Water erosion           |
| 32     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Vegetal degradation     |
| 33     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Water erosion           |
| 34     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Water erosion           |
| 35     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Vegetal degradation     |
| 36     | Moderate                                                                                                             | High                                                                                                        | Low to moderate  | High                 | Hotspot                            | No apparent degradation |
| 37     | Moderate                                                                                                             | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | Water erosion           |
| 38     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Vegetal degradation     |
| 39     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Vegetal degradation     |
| 40     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Vegetal degradation     |
| 41     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Urbanization            |
| 42     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Urbanization            |
| 43     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | No apparent degradation |
| 44     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Urbanization            |
| 45     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Vegetal degradation     |
| 46     | Low                                                                                                                  | High                                                                                                        | Moderate         | Moderate             | Brightspot                         | Water erosion           |
| 47     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Water erosion           |
| 48     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | No apparent degradation |
| 49     | Moderate                                                                                                             | High                                                                                                        | Low to moderate  | High                 | Hotspot                            | Water erosion           |
| 50     | Moderate                                                                                                             | High                                                                                                        | Low to moderate  | High                 | Hotspot                            | Wind erosion            |
| 51     | Low                                                                                                                  | Moderate                                                                                                    | Low to moderate  | Moderate             | Brightspot                         | Water erosion           |
| 52     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Water erosion           |
| 53     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Vegetal degradation     |
| 54     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | High                 | Hotspot                            | Vegetal degradation     |
| 55     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | High                 | Hotspot                            | Urbanization            |
| 56     | Moderate                                                                                                             | High                                                                                                        | Low to moderate  | Moderate             | Brightspot                         | Vegetal degradation     |
| 57     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | Moderate             | Brightspot                         | Water erosion           |
| 58     | Low                                                                                                                  | Moderate                                                                                                    | Moderate to high | Moderate             | Brightspot                         | Wind erosion            |
| 59     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | Moderate             | Brightspot                         | Wind erosion            |
| 60     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Urbanization            |

(Continues)

TABLE 2 (Continued)

| S. No. | Climate profile (based on the cumulative effect of variation in average air temperature, precipitation, and aridity) | Vegetation profile (based on erosion protection, drought resistance, fire risk resistance, and plant cover) | Bowen ratio      | Collective inference | Hotspot/bright spot/potential area | Validation              |
|--------|----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|------------------|----------------------|------------------------------------|-------------------------|
| 61     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | No apparent degradation |
| 62     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Wind erosion            |
| 63     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Wind erosion            |
| 64     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Wind erosion            |
| 65     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | High                 | Hotspot                            | Water erosion           |
| 66     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | High                 | Hotspot                            | No apparent degradation |
| 67     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate to high | High                 | Hotspot                            | Water erosion           |
| 68     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Urbanization            |
| 69     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Wind erosion            |
| 70     | Moderate                                                                                                             | High                                                                                                        | Low to moderate  | High                 | Hotspot                            | Wind erosion            |
| 71     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Water erosion           |
| 72     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Wind erosion            |
| 73     | Moderate                                                                                                             | Moderate                                                                                                    | Moderate         | Moderate             | Brightspot                         | Wind erosion            |
| 74     | Moderate                                                                                                             | High                                                                                                        | Moderate to high | High                 | Hotspot                            | Wind erosion            |
| 75     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Water erosion           |
| 76     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | Water erosion           |
| 77     | Moderate                                                                                                             | High                                                                                                        | Moderate         | High                 | Hotspot                            | No apparent degradation |

### 3.4.2 | From basic definition

From the basic definition, the Bowen ratio was computed for the 77 study locations for the three seasons (Figure 7). For most of the study points and for the majority part of the year, the Bowen ratio lies between the range 2–4, which is the range for semiarid regions. This indicates the presence of the continuous threat of land degradation. Though, for some points, the Bowen ratio falls between 1.5 and 2, which is above the usual range of 0.4–0.8 of tropical forests, that is, it lies between the categories of forests and drylands. This indicates some part of the study area is potentially sensitive towards land degradation.

### 3.5 | Collective inference

Microclimate analysis of the 77 study locations reveals that around 48% of the study area experiences high aridity, 44% experiences moderate aridity whereas around 8% shows low aridity. It sums up to the fact that 92% of the area may be prone to land degradation that may or may not happen depending upon the other factors. When we look at the vegetation profile of the study area, we see that it offers low protection towards erosion, moderate resistance to drought, and high protection against fire. The vegetation cover ranges from predominantly low cover (in winter and in summer seasons) to somewhat high in monsoon season. Taken together, the vegetation condition renders the area vulnerable towards desertification at different intensities at different locations. The LST,  $R_a$ , and NDVI studies reveal that the area is a 'potential area' of land degradation. Also, LST and  $R_a$  values show that the area is mainly vulnerable to salinization and water erosion. In addition to this, the Bowen ratio map signifies that some portion of the study area is under active land degradation.

All of the results are summed up and summarized for the 77 study locations in Table 2. Collective analysis of vegetation and climate patterns along with the results of Bowen ratio approach was used to find out the probable desertification 'hotspots', 'brightspots', and 'potential areas'. Table 2 also shows the actual condition of the area on land according to DSM. This provides validation to the study.

Out of the 77 study points, 38 points (~49%) fall under the category of 'hotspots' another 38 (~49%) as 'brightspots', and one as 'potential area', as is evident from Table 2. When validated from DSM, it is found that a total of 33 of these points are undergoing some kind of active land degradation such as water erosion, wind erosion, vegetal degradation, or some man-made activity covered under class 'urbanization' is going on. The rest of the five points fall under 'no apparent degradation' category. Thus, the error percentage for declaring 'hotspots' through the method discussed here is close to 13%. Majority of the 'brightspots' also show active land degradation, and around 12 of them show 'no apparent degradation'. This indicates that if appropriate measures are not taken up, the currently 'not degraded' areas will also undergo the process of land degradation and desertification. The same is true for the areas under the category of 'potential area'.

## 4 | CONCLUSIONS

Analysis of the climate and vegetation profiles of the study area (Bellary District, Karnataka State, southern India) has provided a clear picture with respect to desertification condition/potential. This analysis was carried out by taking 77 study locations. Climatically, the area is moderately prone to desertification (most of the study locations reveal moderate climate status). The vegetation profile varies between moderate and high risk of desertification. Although the ecosystemic approach of Bowen ratio showed varying status (low, moderate, and high) of desertification, a moderate risk exists for the maximum region. Integrated results of climate, vegetation, and Bowen ratio revealed that out of 77 study locations, 38 are found to be 'brightspots', 38 'hotspots', and one 'potential area' of desertification. The 'hotspots' need urgent action towards rehabilitation and mitigating measures, and 'brightspots' need proper land management. Bowen ratio based monitoring of such areas shall prove highly useful for planning mitigating measures well in time.

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