Environ Monit Assess (2024) 196:536
https://doi.org/10.1007/s10661-024-12707-x

RESEARCH

Spatial and temporal-trend assessment of desertification-sensitive land using the desertification sensitivity index in the provincial Ninh Thuan, Vietnam

Binh Thanh Nguyen · Gai Dai Dinh · Long Ba Le

Received: 2 January 2024 / Accepted: 4 May 2024

Abstract Desertification is a specific land-degrading process, reducing soil productivity and potentially threatening global food security. Therefore, spatially and temporally identifying and mapping desertification-sensitive areas is essential for better management. The current study aimed to (1) assess spatial areas sensitive to desertification and (2) examine the changing tendency of the desertification-sensitive areas over the past 25 years in the provincial Ninh Thuan. The desertification sensitivity index (DSI) was computed based on the Medalus model using 10 quantitative parameters, grouped into the soil, climate, and vegetation quality indexes, computed for the years 1996, 2005, 2010, and 2016. GIS was used to map desertification-sensitive areas associated with five DSI classes. Results showed that classes II and III had the highest area percentage, followed by classes IV and V, and class I. The classes most sensitive to desertification (classes IV and V) covered around 13 to 17%, and classes II and III were 25 to 32% of the total study area, respectively. The coastal areas located in the southeastern parts were more sensitive to desertification than the other parts. Over the four examined periods, the areas of classes IV and V increased while those of classes II and I decreased. These indicated that the study province tended to increase in its desertification sensitivity with a severe increase in the coastal areas over the past 25 years. The key factors involved in these changes could be related the human activities and climate variation, which could be more serious in southeastern areas than in the other areas.

Keywords Desertification-sensitive area · Coastal area · Ninh Thuan · Spatial variation · Temporal variation

Introduction

Drylands, encompassing arid, semi-arid, and dry sub-humid areas, constitute a significant portion of the Earth's surface, covering approximately 45% (Prăvălie, 2016; Prăvălie et al., 2019). Mostly happening on drylands, desertification is a specific land-degradation process caused by climatic change and human activities, reducing biological and agricultural productivity of the lands (Al-Khuzaie et al., 2015; Hadeel et al., 2010; Vani et al., 2015). Desertification could affect about 500 million people worldwide, who are mainly located in South and East Asia, the Circum-Sahara region, and the Middle East including the Arabian Peninsula (Mirzabaev et al., 2019). The livable area would be decreased and poverty would be severely worsened with an increase in the deserted areas (Olukoye & Kinyamario, 2009).

B. T. Nguyen (✉) · G. D. Dinh · L. Ba. Le
Institute of Environmental Science, Engineering and Management, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao, Go Vap District, Ho Chi Minh City, Vietnam
e-mail: nguyenbinh@iuh.edu.vn

Consequently, assessment of the desertification sensitivity may be the first step to developing a suitable strategy for the long run to mitigate the desertification impacts on agricultural productivity and environmental conditions. Desertification could be the consequence caused by combined factors, including soil erosion, vegetation cover, water-related, soil salinization, and alkalization, and climate change (Mirzabaev et al., 2019; Sobhani & Khosravi, 2015). Generally, these factors can be grouped into soil and vegetation factors, and climatic conditions, which were used to assess the desertification sensitivity of drylands (Ma et al., 2015). For this purpose, a framework model was developed by Kosmas et al. (1999) through the Medalus project and was used frequently to quantify the magnitude of the desertification sensitivity of an environmental area. A general principle of this approach relies on the interactions among subfactors, together affecting desertification magnitude. Many studies were implemented to apply the Medalus approach with some modifications to better reflect the nature of study conditions (Coscarelli et al., 2005; Ferrara et al., 2020; Gaetano et al., 2012; Izzo et al., 2013; Mirdeilami et al., 2019; Momirović et al., 2019; Prăvălie et al., 2020). These studies were carried out based on one epoch to examine the spatial change in the land degradation of study areas. In fact, desertification happening in a specific dryland area could be characterized by a two-dimensional model, reflecting spatial and temporal changes. As a result, some others used two epochs to examine the temporal variation of the sensitivity (Bakr et al., 2011; Lee et al., 2019; Symeonakis et al., 2014). Nevertheless, the two epochs of assessments may not truly reflect the temporal trend of the sensitivity to the desertification of study areas. Consequently, it could be better to assess the desertification sensitivity for a longer period with multiple epochs to examine the time-based variation.

Vietnam is located in a tropical region having high annual rainfall. Nevertheless, some parts of the country, such as some central coastal provinces from Quang Binh to Binh Thuan, are insufficient in rainfall, making the areas moderately sensitive to desertification (USDA-NRCS, 2003). Knowing the detrimental impacts of desertification, the Vietnamese government ratified an action program to combat desertification in response to the "United Nations Convention To Combat Desertification" (MARD, 2002). Located in the coastal region with low rainfall and severe drought conditions, the Ninh Thuan province is considered as a semi-arid climate (Hien et al., 2019; Son et al., 2013), and thus as the area most sensitive to desertification, besides the neighboring Binh Thuan province (Le et al., 2013) in Vietnam. Although desertification is generally known as a consequence of combined various-factor impacts (Mirzabaev et al., 2019), the Ministry of Natural Resources and Environment of Vietnam (MONRE, 2012) developed a simple aridity index, based on a ratio of precipitation to potential evapotranspiration to assess desertification level for the Vietnamese territory. This MONRE's model may be scientifically and practically insufficient to assess the desertification level. This was the reason Hien et al., (2019) used the Medalus model to assess the desertification sensitivity of the neighboring Binh Thuan province. To take advantage of the two methods (the MONRE and the Medalus), a combination of these two models could be an appropriate option to assess the desertification sensitivity of the Ninh Thuan province.

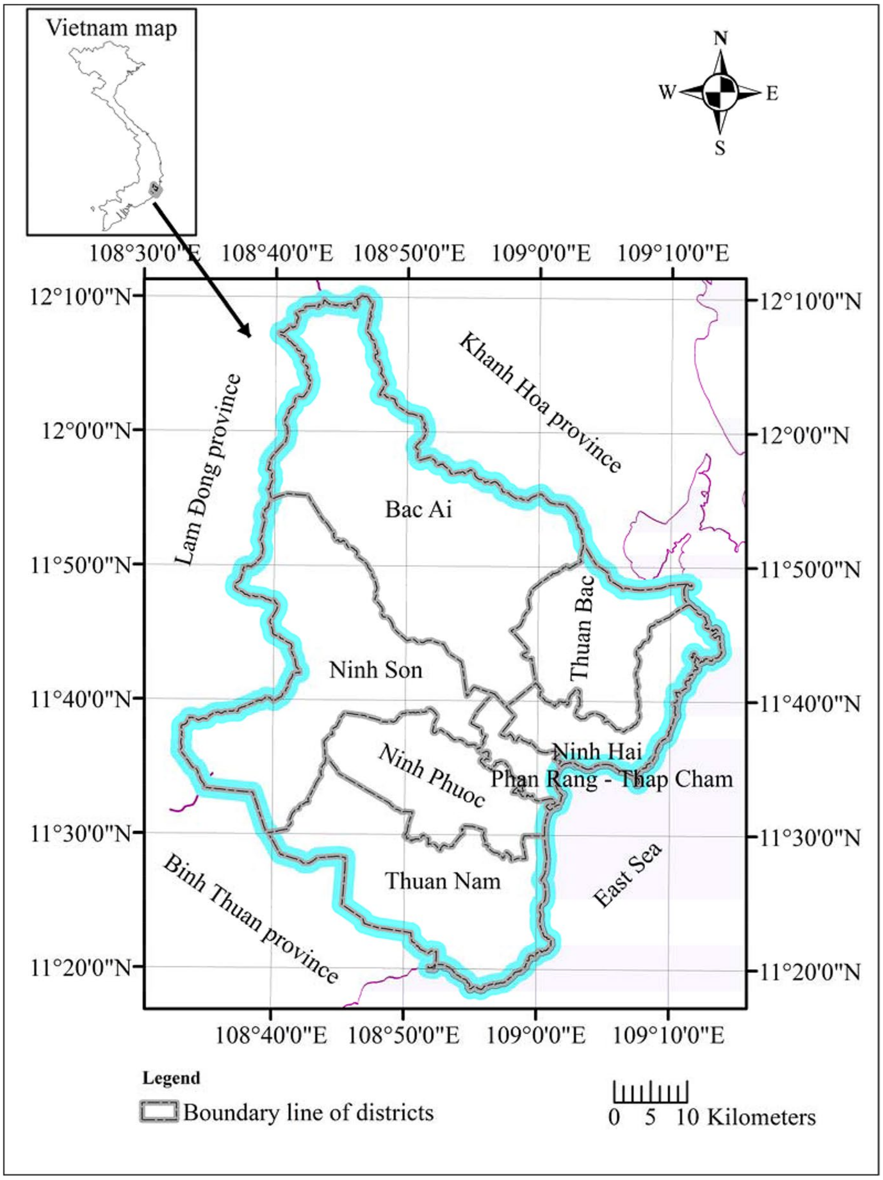
Therefore, the current study was conducted to (1) assess spatial areas sensitive to desertification and (2) examine the changing tendency of the desertification-sensitive areas with the time of the provincial Ninh Thuan, Vietnam. A framework model of a combination of the MONRE and the Medalus model was developed and used for the current study. It was hypothesized that the areas located along the coastal line were more sensitive to desertification than the other areas and that the desertification sensitivity of the study province had increased over the past 20 years.

Materials and methods

The study area

The current study was conducted in the Ninh Thuan Province, located in the south-central coastal region of Vietnam (108°30–109°10′E and 11°20′–12°10′N) (Fig. 1). The province is about 350 km far from Ho Chi Minh City in the South. It is situated next to Khanh Hoa Province in the North, Lam Dong Province in the West, Binh Thuan Province in the South, and the East Sea of Vietnam in the East. The study province has seven administrative units (six districts and a provincial city), covering an area of around

Fig. 1 Map of the study area, the Ninh Thuan province, Vietnam



3358 km^2. It is located in the area where the Truong Son mountain range meets the East Sea. The terrain of the province was lower in the Southeast (the seaside) and gradually higher in the Northwest (the mountainside). The province's territory is surrounded by three mountainous sides with three main landforms of mountains, hilly and mountainous areas, and coastal plain. In particular, the mountains account for 63.2% of the whole province, mostly with an average height of 200 to 1000 m. The hilly and mountainous region accounts for 14.4% and the coastal plain accounts for 22.4% of the natural land area. The province has a tropical climate regime from savanna to semi-arid with high temperatures (average temperature 26–27 °C), dry wind, and strong evaporation. Ninh Thuan weather is divided into two distinct seasons, including rainy (from September to November) and dry seasons (the other months) with an average rainfall of 700–800 mm (Ninh Thuan Government, 2019).

Methods used to assess the desertification-sensitive areas

Overall, a combined approach of the land-degradation investigation method by MONRE, (2012) and the environmental sensitivity area (ESA) method by Kosmas et al. (1999) and Ahmed et al. (2010) was used in the current study. The combined approach was implemented in two sequential steps, of which the first one was to examine whether the study area was rocky or sandy lands (rocky area and sand dunes) (MONRE, 2012), which were classified into rock-desertification-sensitive area or sand-desertification-sensitive area, respectively. The second step was to apply the Medalus model with some modifications to classify the rest area into five classes, based on three main factors, including soil quality index (SQI), vegetation quality index (VQI), and climate quality index (CQI) (Ahmed et al., 2010). As suggested by Farajzadeh and Egbal (2007), the Medalus model should be modified to best suit the study conditions, the current study used three-component indexes because data on the management quality since 1996 were not available, while those of the soil, climate, and vegetation were available. Some authors also used a reduced model with three component indexes (soil, climate, and vegetation indexes) for their studies (Ahmed et al., 2010; Gad and I, 2008; Ogbue et al., 2024). The classification of desertification sensitivity was applied based on the desertification sensitivity index (DSI), which was computed through the equation: $DSI = (SQI * CQI * VQI)^{1/3}$. The desertification sensitivity was divided into five classes (I, II, III, IV, and V), based on DSI values below 1.2 (not sensitive to desertification), 1.2 to below 1.4 (low sensitive to desertification), 14 to below 1.6 (medium sensitive to desertification), 1.6 to below 1.8 (sensitive to desertification), and greater than 1.8 (very sensitive to desertification), respectively. It was also noted that the rock-desertification-sensitive area and sand-desertification-sensitive area were also classified into the class of very sensitive to desertification (MONRE, 2012).

Data collection and quality-index estimation

Soil quality index (SQI) A digital map of soil resources, its characteristics, and FAO-WRB (World Reference Base -World Reference Base) classification were surveyed and provided by the Department of Natural Resources and Environment of the Ninh Thuan Province. Furthermore, we conducted a field trip to reassess and verify the properties of the digital map prior to processing. Four parameters, including soil parent material (SPM), soil depth (SD), soil texture (ST), and slope gradient (SG) (Hadeel et al., 2010), were obtained from the soil map and were used for the current study. A specific land area was evaluated and assigned to receive one of four scores (1, 1.33, 1.66, and 2, and the higher the score the more sensitive to desertification the area) for each of these parameters (more information about how to assign the scores could be found in a study by Hadeel et al., (2010). The soil quality index was computed through the equation: $SQI = (SPM * SD * ST * SG)^{1/4}$. The SQI was classified into five levels of 1, 2, 3, 4, and 5, corresponding to SQI value of below 1.2, from 1.2 to below 1.4, from 1.4 to below 1.6, from 1.6 to below 1.8, and above 1.8, respectively.

Vegetation quality index (VQI) Landsat satellite images of the years 1996 (Landsat 5TM), 2006 (Landsat 7TM), and 2010 (Landsat 7TM) were obtained from http://landsat.usgs.gov/ at a 30-m spatial resolution to process for vegetation quality. For the year 2016, the land cover map of the study area was provided by the Department of Natural Resources and Environment of the Ninh Thuan Province and was verified by our research group. For the input parameters of the soil quality index and vegetation quality index in the most recent observation period, we conducted an additional 80 validation points during field trips. These points were randomly distributed across the seven administrative units comprising the entire study area (Meza Mori et al., 2022). Adjustment of the input parameters was implemented when there were discrepancies between the field trip validation points and the obtained information. Four sub-parameters used to estimate the VQI included fire risk (FR), drought resistance (DR), erosion protection (EP), and cover percentage (CP). The scores for each of these sub-parameters were 1, 1.33, 1.66, and 2 (Hadeel et al., 2010). An individual examined area was processed for each of these parameters to receive one of the above scores associated with individual parameters. The VQI was computed through the equation: $SQI = (FR * DR * EP * CP)^{1/4}$. The VQI was categorized into five levels of 1, 2, 3, 4, and 5, corresponding to VQI value of below 1.2, from 1.2 to below 1.4, from 1.4 to below 1.6, from 1.6 to below 1.8 and above 1.8, respectively.

Climate quality index (CQI) The CQI was computed through two sub-parameters, which are rainfall and aridity index (the ratio between precipitation and PET—potential evapotranspiration). These parameters were collected from eight weather stations (Phan Rang, Nha Ho, Tan My, Quan The, Nhi Ha, Ba Thap, Sông Pha, and Ca Na) within the Ninh Thuan province and two stations of Phan Thiet and Cam Ranh located close but outside the study area for GIS based-spatial interpolation. The rainfall and aridity index were averaged for two periods, from 1978 to 2000 and from 2001 to 2016. The first one was used for the 1996 assessment, and the latter was used for the 2005, 2010, and 2016 assessments. These parameters were used to estimate the CQI through the equation $CQI = (R * AI)^{1/2}$, where R was the rainfall score, and AI was the score of the aridity index (Lee et al., 2019). Similar to the VQI, the CQI was classified into five levels of 1, 2, 3, 4, and 5, corresponding to its value of below 1.2, from 1.2 to below 1.4, from 1.4 to below 1.6, from 1.6 to below 1.8 and above 1.8, respectively.

Mapping the desertification-sensitive area

The Geographic Information System (GIS) method was applied to map the desertification-sensitive area of the study province, using the ArcGIS version 10.6. The digital soil map was used as a base map to be spatially overlaid with the other digital maps associated with climate and vegetation factors. Before that, the ratio of rainfall to PET collected from the eight weather stations was spatially digitalized and interpolated using the nearest-neighbor interpolation in ArcGIS spatial analyst to generate the CQI map for the whole province. The overlaying process was conducted in the order of a soil map, two climate maps (from 1978 to 2000 and from 2001 to 2016), and four vegetation maps from 1996, 2005, 2010, and 2016. Finally, four overlaid digital maps for the years 1996, 2005, 2010, and 2016 were created and data from these maps were exported into an Excel file for further processing, including estimation of area percentage and examination of dependence of the relative percentage of individual DSI classes on examined years through plotting method.

Results

The indexes of soil quality, vegetation quality, and climate quality

The soil quality index (SQI) of the study area was divided into five levels, corresponding to very good quality to very bad quality (Fig. 2 and Table 1). The total area of Bac Ai district was the highest (102722 ha, equal to 30.6% of the total provincial area), and that of Phan Rang-Thap Cham City was the lowest (7919 ha, equal to 2.4%). The districts of Thuan Nam, Ninh Son, Ninh Hai, and Thuan Bac had the highest area percentages (4.9, 4.5, 3.0, and 2.9, respectively) of very bad soil quality (SQI level 5). Ninh Phuoc, Ninh Son, and Thuan Nam districts had the highest area percentage (3.5, 3.5, and 2.5%, respectively) of very good soil quality (SQI level 1) of the seven administrative units. Within individual study units, Bac Ai district had the highest area percentage (20.4%) of the SQI level 3; Ninh Hai district had 3% of the area with SQI level 5; Ninh Phuoc had 3.5% of the area of SQI level 1; Ninh Son had 4.5% of the area of SQI level 5; Phan Rang-Thap Cham had 1.3% of the area of SQI level 1; Thuan Bac had 2.9% of the area of SQI level 5; and Thuan Nam had 4.9% of the area of SQI level 5.

The land cover was examined in 4 years of 1996, 2005, 2010, and 2016 and the vegetation quality index (VQI) of the individual examined years was processed and shown in Fig. 3 and Table 2. Overall, the highest percentage of the study area was categorized into the VQI class I (very good quality) for all four examined years. The area percentage of VQI level 4 (low quality) increased from 1996 (8.73%) to 2016 (26.38%). For all four examined years, with a change of VQI levels 1 to 4, their associated area percentages of the districts of Bac Ai, Ninh Son, and Thuan Nam decreased, while those of Ninh Phuoc and Phan Rang-Thap Cham increased. In the meantime, two districts (Ninh Hai and Thuan Bac) had the area percentage in the year 2016 increased from VQI levels 1 to 4, while they had the percentage in the first 3 years decreased.

Out of five CQI levels (1, 2, 3, 4, and 5), the first three were found in the study area, and level 1 was found to have the highest area percentage (39.28 and 40.23%), followed by the level 3 (33.04 and 31.08%) in 2 years, 1996 and 2010, respectively (Fig. 4 and

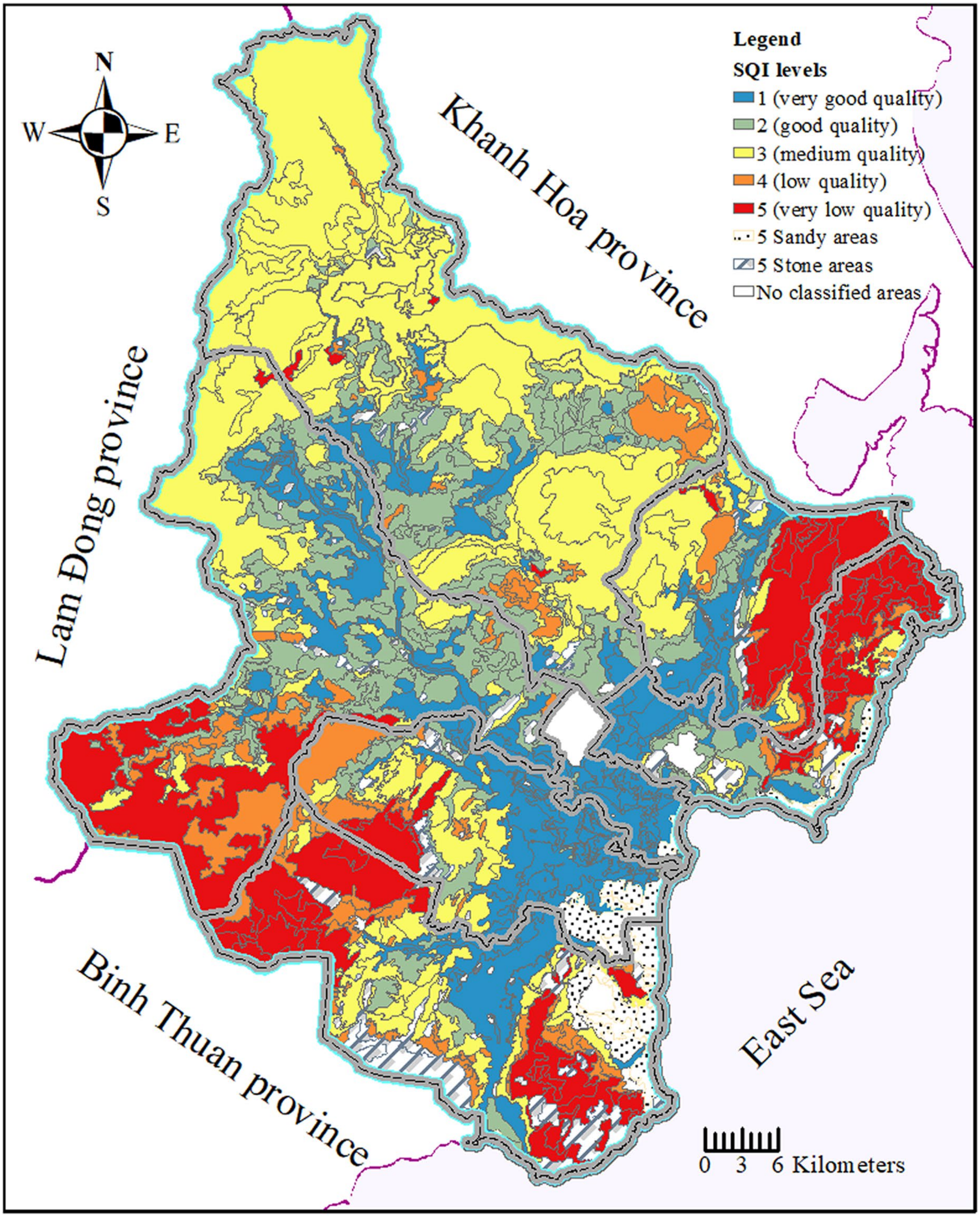


Fig. 2 Spatial variation of individual levels of soil quality index (SQI) of seven administrative units

Table 1 Area percentage of individual levels of soil quality index (SQI) of seven administrative units in the study area. (*PR-TC*, Phan Rang-Thap Cham City)

SQI levels	Bac Ai	Ninh Hai	Ninh Phuoc	Ninh Son	PR-TC	Thuan Bac	Thuan Nam	Sum
Area (ha)								
1	6117.2	4846.5	11,794.8	11,827.9	4395.8	5288.0	7826.1	52,096
2	20,042.2	1995.6	2698.1	22,244.9	246.6	3670.7	1625.6	52,524
3	68,529.7	956.8	6779.1	17,767.4	19.9	9559.2	9110.0	112,722
4	4802.9	1325.0	4387.1	6626.8	151.8	1733.3	5965.5	24,992
5	554.5	10,049.5	3172.6	15,176.3	0.0	9597.6	16,515.3	55,065
Sand area	338.6	1465.2	499.1	363.5	319.0	209.8	2238.4	5434
Rocky area	1142.6	1710.7	1145.0	1229.7	42.9	962.9	7663.5	13,897
No classified area	1194.3	3008.8	3719.5	1944.2	2742.8	804.5	5388.7	18,803
Total area	102,722	25,358	34,195	77,181	7919	31,826	56,333	335,534
Percentage (%)								
1	1.8	1.4	3.5	3.5	1.3	1.6	2.3	15.5
2	6.0	0.6	0.8	6.6	0.1	1.1	0.5	15.6
3	20.4	0.3	2.0	5.3	0.0	2.8	2.7	33.6
4	1.4	0.4	1.3	2.0	0.0	0.5	1.8	7.4
5	0.2	3.0	0.9	4.5	0.0	2.9	4.9	16.4
Sand area	0.1	0.4	0.1	0.1	0.1	0.1	0.7	1.6
Rocky area	0.3	0.5	0.3	0.4	0.0	0.3	2.3	4.1
No classified area	0.4	0.9	1.1	0.6	0.8	0.2	1.6	5.6
Total in %	30.6	7.6	10.2	23.0	2.4	9.5	16.8	100.0

Table 3). Different from the other study units, Bac Ai and Ninh Son Districts decreased in area percentage from CQI level 1 (25.35 and 22.96% for Bac Ai District, and 13.98 and 16.82% for Ninh Son District) to CQI level 3 (0.62 and 1.72% for Bac Ai District and 0.75 and 1.62% Ninh Son District) in 2 years, 1996 and 2010, respectively. In contrast, the other units had the area percentage increasing from CQI levels 1 to 3 in both years. In addition, Fig. 4a and 4b show that a larger portion of areas close or connected to the East Sea was evaluated as semi-arid (CQI level 3) and a larger portion of areas located far from the Sea had lower CQI levels (1 or 3).

Desertification sensitivity index (DSI)-based classification of the study area

In general, five classes of the desertification sensitivity of the study province were identified and shown in Figs. 5, 6, and 7. While class I was distributed relatively randomly (not concentrated) over the study area, class II was located in the areas far from the sea, and class V including sand and rocky areas was more distributed in the areas close or connected to the seaside in all four examined years (Fig. 5a, 5b, 5c, and 5d). Figure 6a shows that class II had the highest area percentage and class V had the lowest area percentage in Bac Ai District. The area percentage of class II decreased from the year 1996 (20.7) to the year 2016 (16.3%), while that of classes IV and V increased from the year 1996 (0.96 and 3.56%) to the year 2016 (0.52 and 1.41%, respectively). The other two classes (I and III) varied from 1.57 to 7.26%, depending on examined years. For Ninh Hai District, class V occupied the largest portion, followed by classes IV, III, II, and I (Fig. 6b). While classes V, IV, and III tended to increase in area percentage, the other classes did not change much for the four examined years. Ninh Phuoc District had the highest area percentage of class III, followed by classes V, IV, II, and I (Fig. 6c). Two classes III and V tended to increase from the year 1996 to the year 2016, while class IV decreased along with the examined year. For Ninh Son District, classes III, IV, and V tended to increase, while the other classes decreased in their area percentage along with the time (Fig. 6d). The area percentage pattern

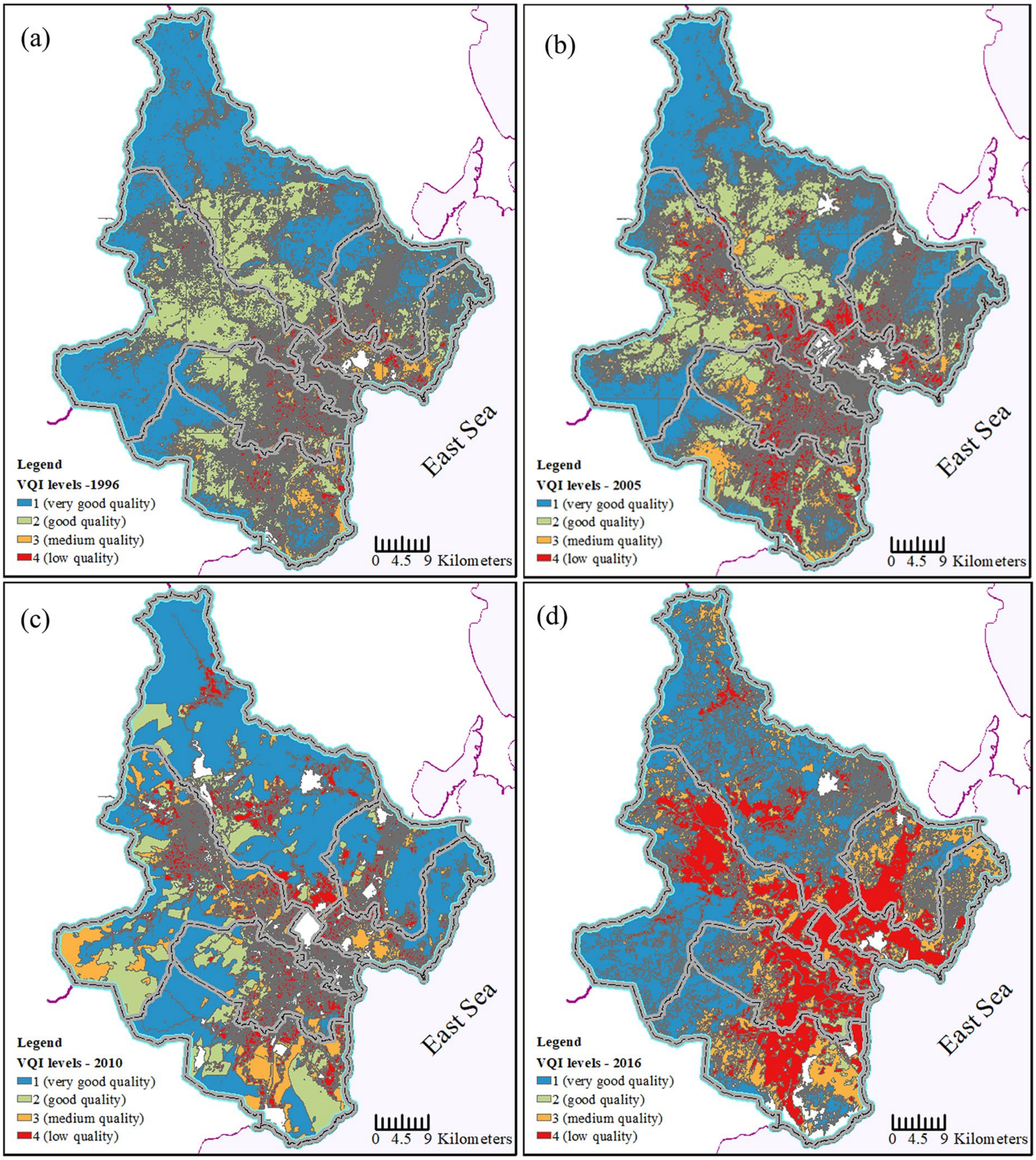


Fig. 3 Spatial variation of individual levels of vegetation quality index (VQI) in 1996 (**a**), 2005 (**b**), 2010 (**c**), and 2016 (**d**) of seven administrative units

of the five classes was ranged in an order (high to low) of class III > II > I > IV > V.

Because Phan Rang-Thap Cham City occupied the smallest portion (2.36%) of the whole province, the area percentage of individual five desertification-sensitive classes for this provincial City was small, varying from zero to 1.18% of the whole province (Fig. 7a). Of the five classes, class III had the highest

Table 2 Area percentage of individual levels of vegetation quality index (VQI) of seven administrative units in the study area. Note: no areas in the study province were found to have the VQI class V. (*PR-TC*, Phan Rang-Thap Cham City); others including sand, rocky, and no-classified areas

Year	VQI levels	Bac Ai	Ninh Hai	Ninh Phuoc	Ninh Son	PR-TC	Thuan Bac	Thuan Nam	Sum
1996	1	18.87	1.52	1.56	9.91	0.01	3.71	3.71	39.30
	2	8.85	1.55	2.93	9.25	0.11	2.63	4.10	29.42
	3	1.29	1.45	1.81	1.46	0.74	1.32	3.06	11.13
	4	0.78	1.20	2.29	1.31	0.57	1.22	1.34	8.73
	Others	0.80	1.84	1.60	1.05	0.92	0.59	4.55	11.36
2005	1	16.17	1.95	0.92	6.78	0.00	3.64	2.91	32.37
	2	8.95	0.99	1.64	6.64	0.00	1.84	2.54	22.61
	3	2.25	1.03	2.35	4.03	0.70	1.27	3.48	15.11
	4	2.07	1.47	3.57	4.18	0.62	1.96	3.11	16.98
	Others	1.15	2.11	1.70	1.35	1.04	0.77	4.73	12.84
2010	1	20.15	3.02	2.16	7.01	0.00	5.03	4.86	42.24
	2	3.47	0.04	1.53	4.06	0.00	0.52	2.44	12.05
	3	1.02	1.26	1.32	5.30	0.29	0.83	2.43	12.46
	4	3.72	1.34	2.87	4.59	0.66	1.98	1.80	16.96
	Others	2.24	1.90	2.29	2.02	1.41	1.12	5.23	16.21
2016	1	18.27	0.49	2.15	11.68	0.00	1.28	4.12	37.98
	2	0.08	0.02	0.15	0.04	0.00	0.17	0.15	0.61
	3	6.05	2.96	2.17	3.99	0.49	4.38	3.59	23.62
	4	5.08	2.45	4.39	6.60	1.16	3.04	3.66	26.38
	Others	1.12	1.63	1.33	0.68	0.71	0.61	5.26	11.33

area percentage, which tended to decrease slightly (from 1.21 to 1.18%) over the examined years. Class II decreased in its area percentage from 0.14 in the year 1996 to almost zero in the last three examined years. Classes V and IV tended to increase in their area percentages for the last two examined years, while class I was almost zero in its area percentages for all four years. Of the five DSI classes of Thuan Bac District, class IV was the highest, followed by classes III, V, II, and I in their area percentage (Fig. 7b). The area percentage of classes III and I tended to decrease from 2.88 and 0.25 (the year 1996) to 2.74 and 0.01 (%, the year 2016, respectively), while that of class II tended to increase from 0.72 (the year 1996) to 1.11 (%, the year 2016). Thuan Nam District had the highest area percentage of class V, followed by classes IV, III, II, and I. Classes V and III had the area percentage increased from 6.6 and 3.1 in the year 1996 to 7.39 and 3.6 (%) in the year 2016, respectively, while classes IV and II had the percentage increased from 4.8 and 0.71 in the year 1996 to 3.3 and 0.14 (%) in the year 2016, respectively (Fig. 7c).

For the whole study province, classes II and III had the highest and similar area percentage, varying from 25 to 32%, followed by the other classes IV and V, varying from 13 to 17%, and then class I, varying from 4.0 to 5.8% (Fig. 7d). Along with the time (1996 to 2016), the area percentage of classes IV and V increased from 13.9 and 14.3 to 17.4 and 17.6 (%), respectively. Meanwhile, classes II and I had the area percentage decreased from 32 and 5.8 to 25 and 4.9 (%) respectively. Class III had the percentage increased slightly from 28.4 to 30.8% with the increasing examined year.

Discussion

Desertification-sensitive areas

A few models were used to assess the desertification sensitivity of dryland in Vietnam, such as that issued by MONRE (2012) and that used by Hien et al. (2019). While the former was relatively simple

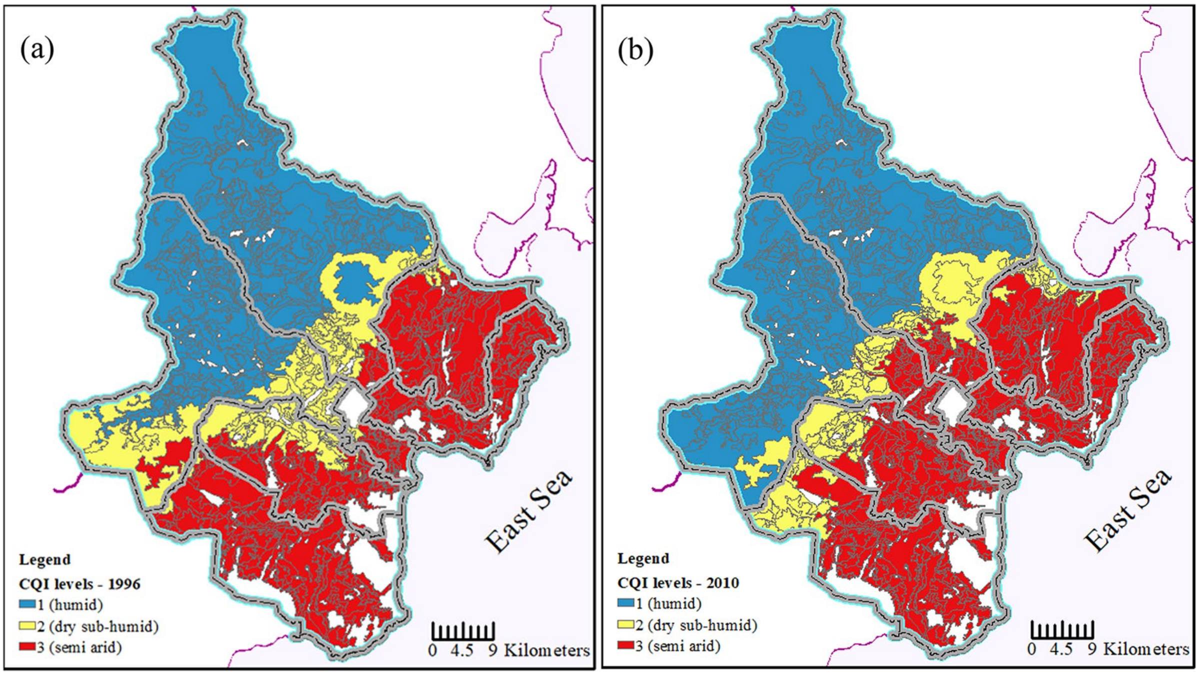


Fig. 4 Spatial variation of individual levels of the climate quality index (CQI) in 1996 (**a**) and 2010 (**b**) of seven study administrative units

Table 3 Area percentage of individual levels of climate quality index (CQI) of seven administrative units in the study area. Note: no areas in the study province were found to have CQI classes IV and V. (*PR-TC*, Phan Rang-Thap Cham City); others including sand, rocky, and no-classified areas

Year	CQI levels	Bac Ai	Ninh Hai	Ninh Phuoc	Ninh Son	PR-TC	Thuan Bac	Thuan Nam	Sum
1996	1	25.35	0.00	0.03	13.89	0.00	0.00	0.00	39.28
	2	3.82	0.00	3.55	7.29	0.32	0.78	0.49	16.25
	3	0.62	5.71	5.00	0.75	1.11	8.11	11.74	33.04
	Others	0.80	1.84	1.60	1.05	0.92	0.59	4.55	11.36
2010	1	22.96	0.00	0.20	16.82	0.00	0.05	0.20	40.23
	2	3.68	0.00	2.30	2.54	0.00	1.36	2.52	12.40
	3	1.72	5.65	5.39	1.61	0.94	6.94	8.82	31.08
	Others	2.24	1.90	2.29	2.02	1.41	1.12	5.23	16.21

and based on a ratio of rainfall to PET (potential evapotranspiration), the latter was based on the principle of the Medalus approach (Kosmas et al., 1999), including soil, climate, vegetation, water management, and human pressure factors. The current study used a combination of these two models with some simplified modifications to assess the desertification sensitivity of the Ninh Thuan Province. After classifying the sand and rocky area using MONRE's approach, the desertification sensitivity assessment was carried out using the desertification sensitivity index (DSI), which was originally based on the principle of the Medamus project model (Kosmas et al., 1999). An overall assumption of the model was that an area classified as very sensitive to desertification could be a consequence of several combined indexes, commonly including the

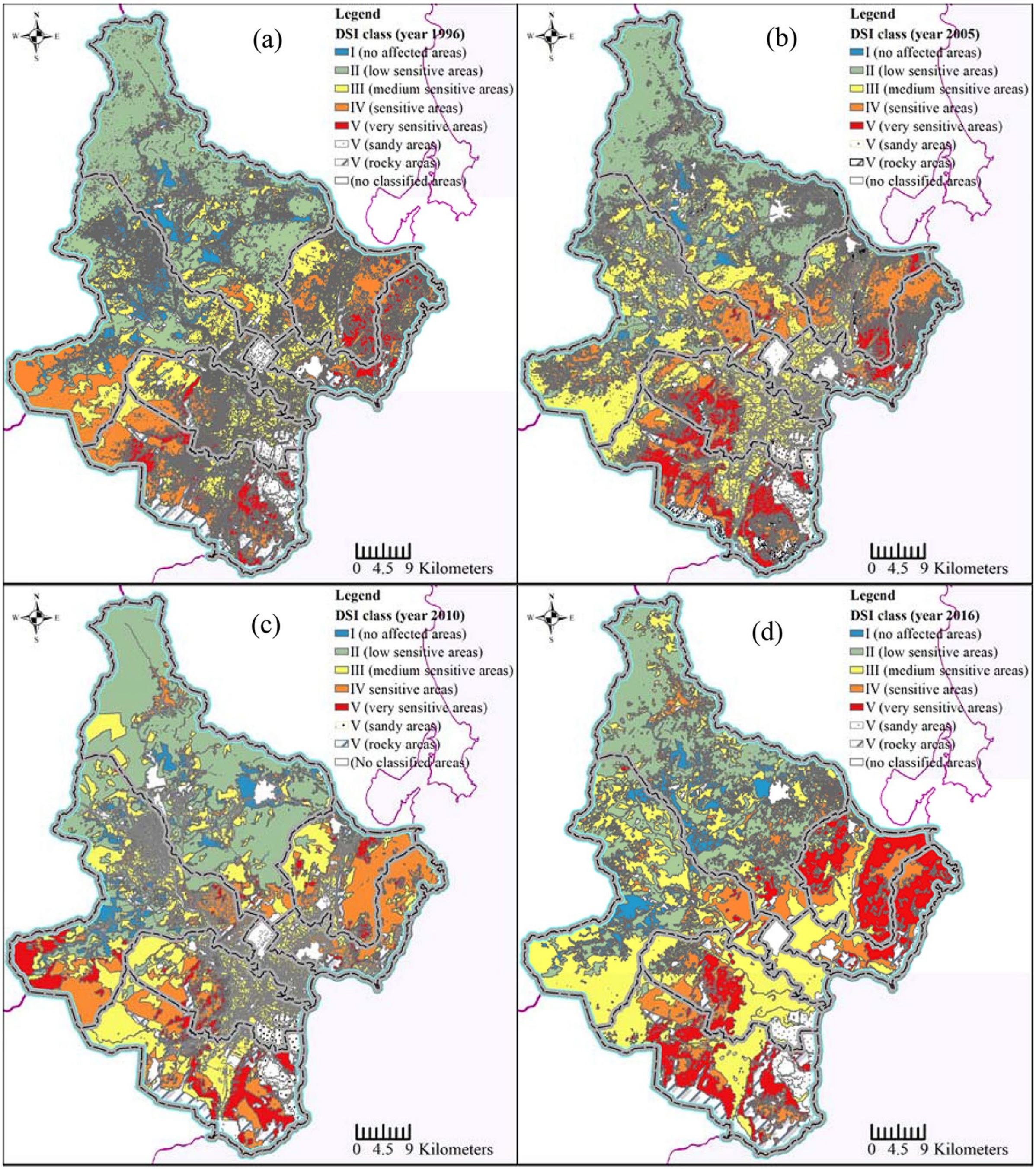


Fig. 5 Spatial variation of individual classes of the desertification sensitivity index (DSI) in 1996 (**a**), 2005 (**b**), 2010 (**c**), and 2016 (**d**)

soil quality index, vegetation quality index, and climatic quality index (Ahmed et al., 2010).

The current study found that the desertification-sensitive areas associated with individual five DSI classes varied greatly with administrative units of the study area, and classes II and III occupied the largest area, followed by classes IV and V, and finally class I (Fig. 7d). Around 28 to 35% of the total study

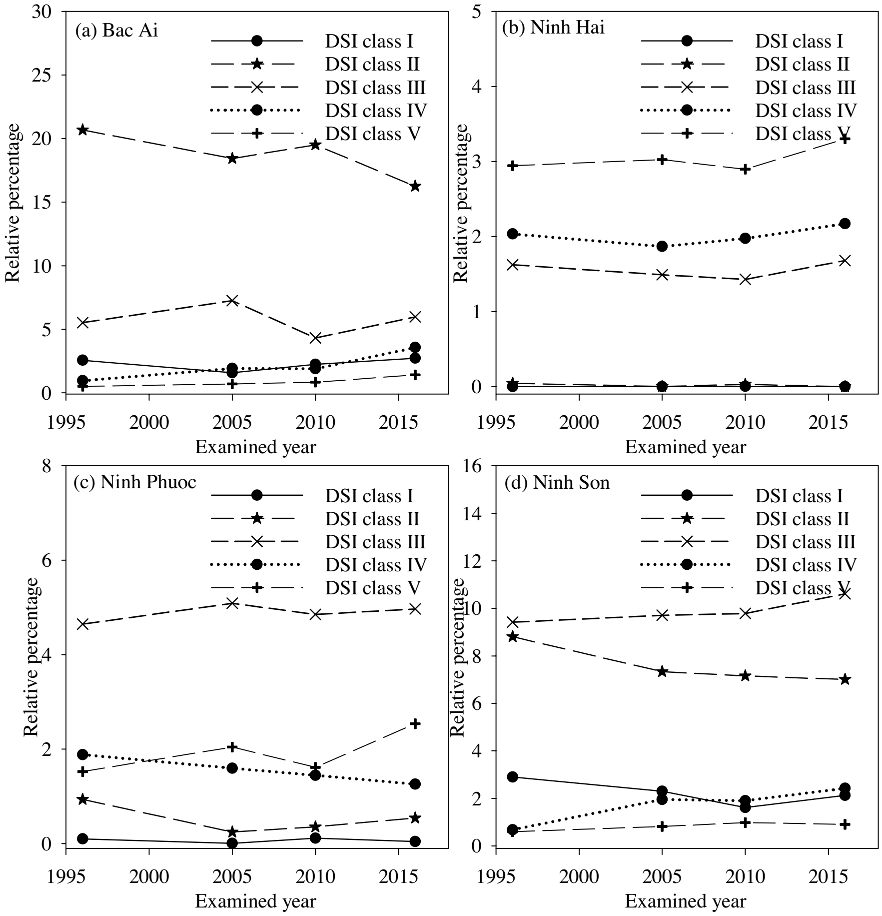
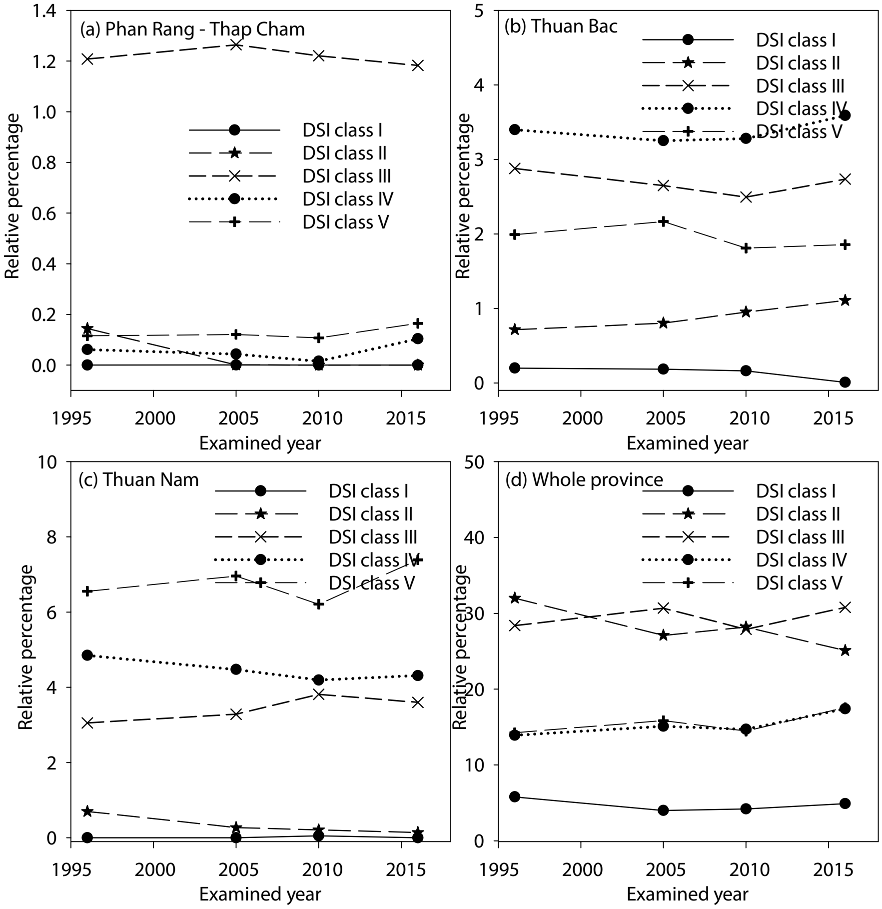


Fig. 6 Variation in area percentage of five DSI classes of Bac Ai (**a**), Ninh Hai (**b**), Ninh Phuoc (**c**), and Ninh Son (**d**) along with examined years of the study areas. Note: class V including very sensitive areas, sand areas, and rocky areas

area was grouped into classes IV and V, which indicated that a considerable portion of the study area was highly sensitive to desertification. Nevertheless, the area percentage (14 to 17%) classified as very sensitive to desertification (class V) of the current study area was similar to that (around 14%) of the neighboring Binh Thuan province identified by Hien et al. (2019). The desertification sensitivity varied greatly from location to location, depending on the local conditions. With a similar approach, Egyptian territory was reported to have around 86% of the study area sensitive to desertification (Ahmed et al., 2010); southeast Morocco had 50.34% classified as high and very high sensitive areas (Lamqadem et al., 2018). Sobhani and Khosravi (2015) reported that around 39.39% of the Chehel-chai basin in the North of Iran was highly sensitive to desertification. These indicated that the local soil, vegetation, and climatic factors, contributing to the desertification sensitivity in different studies, varied greatly from location to location.

Three factors, including soil, vegetation, and climatic factors were commonly included to assess dryland areas sensitive to desertification. For the current study, the soil quality index was computed through four soil parameters, including parent material, soil depth, soil texture, and slope. These parameters of the study area could vary slightly over the past 20 years because they are inherent properties of a particular soil. In addition, the current study also found that a considerable portion of the study area was occupied by sand dunes and rocky mountains/hills (5–7%), which were classified as very sensitive to desertification (MONRE, 2012). Rainfall was an important factor in affecting the desertification sensitivity of Mongolian territory (Lee et al., 2019). The climatic factor was computed based on annual rainfall and the aridity index. The rainfall in the current study varied

Fig. 7 Variation in area percentage of five DSI classes of Phan rang-Thap Cham (**a**), Thuan Bac (**b**), Thuan Nam (**c**), and the whole province (**d**) along with examined years



from around 600 to above 1000 mm, which could be considered to be low in supplying water resources. Tsesmelis et al. (2018) indicated that annual rainfall, varying from 367 to 2070 mm, was an important factor in determining the vulnerability to the desertification of Greece. The low annual rainfall in the current study could be one of the few important reasons for determining the desertification sensitivity of the study area.

Different from the two above factors, the vegetation factor was more likely involved in human activities, which may cause forests converted or deforested for various purposes, such as agricultural development, wood harvest, and infrastructure extension (Shvidenko, 2008). Conducting a study to map the environmental sensitivity area in Čukarica of Serbia, Momirović et al. (2019) concluded that vegetation quality was one of the two factors highly influencing the land sensitivity to desertification. The vegetation quality could be involved in land covers, including agricultural lands (paddy, fruit, and vegetable lands), natural forests, planted forests, shrubland, and barren lands. In the current study, the VQI was computed from four sub-factors, reflecting the characteristics of vegetation, including erosion protection, drought resistance, land cover percentage, and fire risk. The main vegetation of the study area was annual crops (29%), broadleaf forests (21%), shrubs and bushes land (12.5%), and others. Areas with poor vegetation quality were found to be highly sensitive to desertification in Cabo Verde Archipelago, West African coast (Pina et al., 2015), and Egypt (Shalaby et al., 2012). In the current study, the areas covered with annual crops were those located along the coastline in the southeastern parts, which were more sensitive to desertification than the others.

The spatial trend of desertification-sensitive areas

The desertification-sensitive areas of classes IV and V were more concentrated in the areas along the coastline (Fig. 5a, 5b, 5c, and 5d). This indicated that the areas close to the seaside were more sensitive to desertification than the areas located far from the seaside, confirming our first hypothesis. This spatial variation could be related to the climatic factor and vegetation factor, which were better (high quality equal low-quality index) in the far-coastline areas. In the current study, rainfall (*P*) varied from 700 to 800 mm in the areas along the coastline of the southeastern part but increased to over 1000 mm in the northwestern parts (far from the seaside). In contrast, the annual potential evapotranspiration (PET) was higher in the seaside-close area and increased slightly in the area far from the coastline. Consequently, the ratio of precipitation to PET (Hadeel et al., 2010) gradually increased from the seaside-close area to the areas far from the seaside, possibly explaining the area percentage of the very sensitive-to-desertification class (class V) in the southeastern parts higher than that in the northwestern parts (Fig. 5).

For the vegetation factor, the areas along the coastline were mainly covered with sand/rocky soil, barren lands, and annual crops. These lands are highly sensitive to desertification due to their susceptibility to fire risk (crop residue), erosion (agricultural activity and barren/sandy soil), drought resistance (annual crops), and low cover percentage (sand/rocky soil and barren lands). In contrast, the areas located on the southwestern side were covered with natural and/or planted forests of broadleaf and some shrubs and bushes. These vegetation types were evaluated to have high quality (low VQI). These also indicated that human activities such as agricultural production, industrial production, and transportation could be an important factor affecting the vegetation index of the study area. The high human population in the areas close to the seaside could be the main cause of the low vegetation quality in the areas.

Temporal trend of desertification-sensitive areas

Based on two examined periods, Symeonakis et al. (2014) reported that some parts of the whole study area of Lesvos Island increased while others decreased in the area of the class sensitive to desertification. The authors also pointed out that the sensitivity to the desertification of the study area was related to human activities such as demographic pressure. Based on four examined years, the current study found that the area percentage of the classes most sensitive to desertification (classes IV and V) increased from the year 1996 to the year 2016, and the increasing rate for the whole study area was 0.16 and 0.13% per year for class IV and class V, respectively. It was also interesting that all seven administrative units of the study area, except Thuan Bac District, had area percentage of class V (the most sensitive to desertification) increased from the year 1996 to the year 2016 (positive increasing rate). In addition, all four study units, connected to the coastline (Thuan Nam, Ninh Phuoc, Phan Rang-Thap Cham, and Ninh Hai), had an area percentage of class V increasing for the examined periods. This indicated that the areas along the seaside tended to increase in their sensitivity to desertification, relative to the other areas. Class IV, the second most sensitive to desertification, was found to increase in its area percentage of the five administrative units (Bac Ai, Ninh Hai, Ninh Son, Phan Rang-Thap Cham, and Thuan Bac). These additionally suggested that the study province tended to increase in its sensitivity to desertification over the past years and could be for the coming years, confirming our second hypothesis. In a nearby province of Ninh Thuan, the Binh Thuan province was projected to increase in desertification-sensitive areas from 14.4% in 2010 to 31.9% in 2050 (Hien et al., 2019). The authors attributed the desertification sensitivity of the study area to some factors including drought, soil types, human impact, and water management. The current study revealed that human activities and climate variation over the study area could be the main factors determining the desertification sensitivity of Ninh Thuan province.

The current study showed the spatial and temporal variation in land degradation in the Ninh Thuan province, based on the Medalus model with three component indexes. The current assessment did not incorporate the management quality index (MQI), potentially affecting certain areas, compared to the current findings. MQI comprises three main parameters, which are land use and intensity of land use, overgrazing, and fire (Kosmas et al., 1999). While these parameters are not directly evaluated, they could be partially reflected through the VQI, which is composed of fire risk, drought resistance, erosion protection, and cover percentage. These elements strongly correlate with land use and intensity and fire in MQI. Overgrazing is likely minimal in the current study area in terms of accelerating land desertification because the area is low in rainfall and livestock in the province is not the main livelihood, compared to the other agricultural activities. Therefore, incorporating MQI may result in marginal alterations to desertification sensitivity areas in the study area.

Conclusions

Of the five classes identified through the desertification sensitivity index, classes II and III had the highest and similar area percentage, followed by classes IV and V, and then class I. The classes most sensitive to desertification (classes IV and V) of the study area occupied around 13 to 17%, and classes II and III were 25 to 32%. The coastal areas located in the southeastern parts of the province were more sensitive to desertification than the other parts, such as those located in the northwestern parts. Along the 4 examined years, the areas of classes IV and V increased while those of classes II and I decreased. These indicated that the study area tended to increase in its desertification sensitivity, with a severe increase in the coastal areas. The key factors involved in these tendencies could be related the human activities and climate variation, which could be more serious in the southeastern areas than in the other areas. The findings also indicated that some parameters such as fire risk, drought resistance, erosion protection, and cover percentage, which are potentially influenced by anthropogenic activities, need to be protected to reduce the desertification risk.

Acknowledgements This research is supported by Industrial University of Ho Chi Minh City (IUH) under grant number 108/HD-DHCN. The authors are grateful to the Industrial University of Ho Chi Minh City (IUH) and the Institute of Environmental Science, Engineering, and Management (IESEM) of IUH. Many thanks are given to the staff and students at IESEM for their help with field trips.

Author contribution Binh Thanh Nguyen: Conceptualization, Visualization, Writing - original draft, Writing - review & editing; Gai Dai Dinh: Methodology, Writing - original draft,; Long Ba Le: Formal analysis, Investigation, Resources, Software; All authors reviewed the manuscript.

Funding This research is supported by Industrial University of Ho Chi Minh City (IUH) under grant number 108/HD-DHCN.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Ahmed, A. A., Gad, A., & Refat, A. (2010). Use of GIS and remote sensing for environmental sensitivity assessment of North Coastal Part Egypt. *Journal of American Science, 6*, 632–646.

Al-Khuzaie, M. M., Elnaggar, A. A., & Mowafy, M. Z. M. E. Z. (2015). Assessments of environmental sensitivity to desertification in north Sinai, Egypt using remote sensing and GIS techniques. *International Journal of Scientific & Engineering Research, 6*(6), 806.

Bakr, N., Weindorf, D., Bahnassy, M., & El-Badawi, M. (2011). Multi-temporal assessment of land sensitivity to desertification in a fragile agro-ecosystem: Environmental indicators. *Ecological Indicators, 15*, 271–280. https://doi.org/10.1016/j.ecolind.2011.09.034

Coscarelli, R., Minervino, I., & Sorriso-Valvo, M. (2005). Methods for the characterization of areas sensitive to desertification: An application to the Calabrian territory, Italy. *IAHS-AISH Publication, 299*, 23–30.

De Pina, T. J., Baptista, I., Ferreira, A. J. D., Amiotte-Suchet, P., Coelho, C., Gomes, S., Amoros, R., Dos Reis, E. A., Mendes, A. F., Costa, L., Bentub, J., & Varela, L. (2015). Assessment and mapping the sensitive areas to desertification in an insular Sahelian mountain region Case study of the Ribeira Seca Watershed, Santiago Island, Cabo Verde. *CATENA, 128*, 214–223. https://doi.org/10.1016/j.catena.2014.10.005

Farajzadeh, M., & Egbal, M. (2007). Evaluation of MEDALUS model for desertification hazard zonation using GIS; study area: Iyzad Khast Plain Iran. *Pakistan Journal of Biological Sciences: PJBS, 10*, 2622–2630. https://doi.org/10.3923/pjbs.2007.2622.2630

Ferrara, A., Kosmas, C., Salvati, L., Padula, A., Mancino, G., & Nole, A. (2020). Updating the MEDALUS-ESA framework for worldwide land degradation and desertification assessment. *Land Degradation and Development*. https://doi.org/10.1002/ldr.3559

Gad A-A, Lofty I. (2008) Use of remote sensing and GIS in mapping the environmental sensitivity areas for desertification of Egyptian territory. eEarth Discussions 3. https://doi.org/10.5194/eed-3-41-2008

Gaetano L, Todorovic M, Liuzzi G. (2012). A GIS-based approach for desertification risk assessment in Apulia Region, SE Italy. Physics and Chemistry of The Earth

- PHYS CHEM EARTH 49. https://doi.org/10.1016/j.pce.2011.05.007

Hadeel, A. S., Jabbar, M. T., & Chen, X. (2010). Application of remote sensing and GIS in the study of environmental sensitivity to desertification: A case study in Basrah Province, southern part of Iraq. *Applied Geomatics, 2*, 101–112. https://doi.org/10.1007/s12518-010-0024-y

Hien, L., Gobin, A., & Huong, P. (2019). Spatial indicators for desertification in southeast Vietnam. *NHESS, 19*, 2325–2337. https://doi.org/10.5194/nhess-19-2325-2019

Izzo, M., Araujo, N., Aucelli, P., Maratea, A., & Sánchez, A. (2013). LAND sensitivity to desertification in the dominican republic: An adaptation of the ESA methodology. *Land Degradation and Development, 24*(486), 498. https://doi.org/10.1002/ldr.2241

Kosmas, C., Kirkby, M., & Geeson, N. (1999). The Medalus project Mediterranean desertification and land use. Project ENV4 CT 95 0119. European environment and climate research programme, Online. Retrieved from https://www.researchgate.net/publication/262374822_Methodology_for_mapping_Environmentally_Sensitive_Areas_ESAs_to_desertification_'The_Medalus_Model. Accessed 9 May 2024.

Lamqadem, A. A., Pradhan, B., Saber, H., & Rahimi, A. (2018). Desertification sensitivity analysis using MEDALUS Model and GIS: A case study of the Oases of Middle Draa Valley, Morocco. *Sensors (basel, Switzerland), 18*, 2230. https://doi.org/10.3390/s18072230

Le, T. H., Gobin, A., & Hens, L. (2013). Risk sssessment of desertification for Binh Thuan province, Vietnam. Human and Ecological Risk Assessment: An. *International Journal, 19*, 1544–1556. https://doi.org/10.1080/10807039.2012.716688

Lee, E. J., Piao, D., Song, C., Kim, J., Lim, C.-H., Kim, E., Moon, J., Kafatos, M., Lamchin, M., Jeon, S. W., & Lee, W.-K. (2019). Assessing environmentally sensitive land to desertification using MEDALUS method in Mongolia. *Forest Science and Technology, 15*, 210–220. https://doi.org/10.1080/21580103.2019.1667880

Ma, H., Jiang, X., Wang, X., & Cao, S. (2015). What has caused desertification in China? *Science and Reports, 5*, 15998. https://doi.org/10.1038/srep15998

Meza Mori, G., Torres Guzmán, C., Oliva-Cruz, M., Salas López, R., Marlo, G., & Barboza, E. (2022). Spatial analysis of environmentally sensitive areas to soil degradation using MEDALUS model and GIS in amazonas (Peru): An alternative for ecological restoration. *Sustainability, 14*, 14866.

Mirdeilami, S. Z., Moradi, E., & Pessarakli, M. (2019). The role of local settlements in combating desertification of Isfahan's Desert Rangelands. *Journal of Rangeland Science, 9*, 202–218.

Mirzabaev, A., Wu J., Evans J., García-Oliva, F., Hussein, I. A. G., Iqbal M. H., Kimutai, J., Knowles, T., Meza, F., Nedjraoui, D., Tena, F., Türkeş, M., Vázquez, R.J., & Weltz, M. (2019) Desertification. Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley (Eds.), https://doi.org/10.1017/9781009157988.005

MARD MoAaRD. (2002). Vietnam national action programme to combat desertification. Retrieved from https://www.unccd.int/sites/default/files/naps/vietnam-eng2002.pdf. Accessed 9 May 2024.

Momirović, N., Kadović, R., Perović, V., Marjanović, M., & Baumgertel, A. (2019). Spatial assessment of the areas sensitive to degradation in the rural area of the municipality Čukarica. *International Soil and Water Conservation Research, 7*, 71–80. https://doi.org/10.1016/j.iswcr.2018.12.004

MONRE. (2012). Ministry of natural resources and environment, Thông tư Ban hành quy định kỹ thuật điều tra thoái hóa đất, thông tư số 14/2012/TT-BTNMT, Hà Nội, ngày 26 tháng 11 năm 2012. Retrieved from https://vupc.monre.gov.vn/dat-dai/3617/thong-tu-so-14-2012-tt-btnmt-ngay-26-11-2012-cua-bo-truong-bo-tai-nguyen-va-moi-truong-ban-hanh-quy. Accessed 9 May 2024.

Ninh Thuan Government. (2019). Natural and social conditions. Retrieved from https://ninhthuan.vietnam.vn/dieu-kien-tu-nhien-va-xa-hoi/. Accessed 9 May 2024.

Ogbue, C., Igboeli, E., Ajaero, C., Ochege, F. U., Yahaya, I. I., Yeneayehu, F., You, Y., & Wang, Y. (2024). Remote sensing analysis of desert sensitive areas using MEDALUS model and GIS in the Niger River Basin. *Ecological Indicators, 158*, 111404. https://doi.org/10.1016/j.ecolind.2023.111404

Olukoye, G. A., & Kinyamario, J. I. (2009). Community participation in the rehabilitation of a sand dune environment in Kenya. *Land Degradation and Development, 20*, 397–409. https://doi.org/10.1002/ldr.932

Prăvălie, R. (2016). Drylands extent and environmental issues a global approach. *Earth-Science Reviews, 161*, 259–278. https://doi.org/10.1016/j.earscirev.2016.08.003

Prăvălie, R., Bandoc, G., Patriche, C., & Sternberg, T. (2019). Recent changes in global drylands: Evidences from two major aridity databases. *CATENA, 178*, 209–231. https://doi.org/10.1016/j.catena.2019.03.016

Prăvălie, R., Patriche, C., Săvulescu, I., Sîrodoev, I., Bandoc, G., Sfîcă, L. (2020). Spatial assessment of land sensitivity to degradation across Romania. A quantitative approach based on the modified MEDALUS methodology. Catena 187:104407. https://doi.org/10.1016/j.catena.2019.104407

Shalaby, A., Ali, R. R., & Gad, A. (2012). A GIS-based model for desertification sensitivity assessment case study: Inland Sinai and Eastern Desert Wadies. *International Journal of Sciences: Basic and Applied Research, 1*, 1–11. https://www.crdeepjournal.org/wp-content/uploads/2011/12/1.IJBAS_Vol._1_1_.pdf

Shvidenko, A. (2008). Deforestation. In: Jørgensen, S. E., Fath, B. D. (eds.) Encyclopedia of ecology (Academic Press, Oxford), pp. 853–859. https://doi.org/10.1016/B978-008045405-4.00586-3

Sobhani, A., Khosravi., H. (2015). Assessing environmental sensitivity areas to desertification in North of Iran Current World Environment 10. https://doi.org/10.12944/CWE.10.3.19

Son, HT., Lan, VTT., Ha, BH. (2013). The application of mike basin model to determine water balance in Cai Phan Rang river basin. Vietnam Journal of Earth Sciences 35. https://doi.org/10.15625/0866-7187/35/1/3041

Symeonakis, E., Karathanasis, N., Koukoulas, S., & Panagopoulos, G. (2014). Monitoring sensitivity to land degradation and desertification with the environmentally sensitive area Index: The case of Lesvos Island. *LDD*. https://doi.org/10.1002/ldr.2285

Tsesmelis, D., Karavitis, C., Oikonomou, P., Alexandris, S., & Kosmas, C. (2018). Assessment of the vulnerability to drought and desertification characteristics using the standardized drought vulnerability index (SDVI) and the environmentally sensitive areas index (ESAI). *Resources, 8*, 6. https://doi.org/10.3390/resources8010006

USDA-NRCS. (2003). United States Department of Agriculture – Natural resources conservation service. Global desertification vulnerability map. Retrieved from https://en.m.wikipedia.org/wiki/File:Desertification_map.png. Accessed 9 May 2024.

Vani, K., Murugaiya, R., Ramakrishnan, S., Ramalakshmi, M., & Mariappan, M. (2015). Assessment of environmentally sensitive area and desertification severity using GIS for an Indian Region - Virudhunagar District, Tamil Nadu. *Indian Journal of Geo-Marine Sciences, 44*, 1734–1741.