Monitoring desertification processes in Mongolian Plateau using MODIS tasseled cap transformation and TGSI time series postprint

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Abstract

Most remote sensing studies assess the desertification using vegetation monitoring method. But it has the insufficient precision of vegetation monitoring for the limited vegetation cover of the desertification region. Therefore, it offers an alternative approach for the desertification research to assess sand dune and sandy land change using remote sensing in the desertification region. In this study, the indices derived from the well-known tasseled cap transformation (TCT), tasseled cap angle (TCA), disturbance index (DI), process indicator (PI), and topsoil grain size index (TGSI) were integrated to monitor and assess the desertification at the thirteen study sites including sand dunes and sandy lands distributed in the the Mongolian Plateau (MP) from 2000 to 2015. A decision tree was used to classify the desertification on a regional scale. The average overall accuracy of 2000, 2005, 2010 and 2015 desertification classification was higher than 90%. Results from this study indicated that integration of the advantages of TCA, DI and TGSI could better assess the desertification. During the last 16 years, Badain Jaran Desert, Tengger Desert, and Ulan Buh Desert showed a relative stabilization. Otindag Sandy Land and the deserts of Khar Nuur, Ereen Nuur, Tsagan Nuur, Khongoryn Els, Hobq, and Mu Us showed a slow increasing of desertification, whereas Bayan Gobi, Horqin and Hulun Buir sandy lands showed a slow decreasing of desertification. Compared with the other 11 sites, the fine sand dunes occupied the majority of the Tengger Desert, and the coarse sandy land occupied the majority of the Horqin Sandy Land. Our findings on a three or four years' periodical fluctuated changes in the desertification may possibly reflect changing precipitation and soil moisture in the MP. Further work to link the TCA, DI, TGSI, and PI values with the desertification characteristics is recommended to set the thresholds and improve the assessment accuracy with field investigation.

Full Text

Preamble

Monitoring Desertification Processes in the Mongolian Plateau Using MODIS Tasseled Cap Transformation and TGSI Time Series

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Abstract: Most remote sensing studies assess desertification through vegetation monitoring methods, but these approaches suffer from insufficient precision in sparsely vegetated desertification regions. This limitation suggests an alternative strategy: evaluating sand dune and sandy land change using remote sensing in desertification-prone areas. In this study, indices derived from tasseled cap transformation (TCT)—including tasseled cap angle (TCA), disturbance index (DI), process indicator (PI), and topsoil grain size index (TGSI)—were integrated to monitor and assess desertification across thirteen sand dune and sandy land sites distributed throughout the Mongolian Plateau (MP) from 2000 to 2015. A decision tree was employed for regional-scale desertification classification, achieving average overall accuracies exceeding 90% for 2000, 2005, 2010, and 2015. Results demonstrated that integrating the complementary strengths of TCA, DI, and TGSI significantly improved desertification assessment. Over the 16-year study period, the Badain Jaran, Tengger, and Ulan Buh deserts exhibited relative stabilization. Otindag Sandy Land and the deserts of Khar Nuur, Ereen Nuur, Tsagan Nuur, Khongoryn Els, Hobq, and Mu Us showed slowly increasing desertification, whereas Bayan Gobi, Horqin, and Hulun Buir sandy lands exhibited slowly decreasing desertification. Compared with the other eleven sites, fine sand dunes dominated the Tengger Desert, while coarse sandy land predominated in the Horqin Sandy Land. Our findings of three-to-four-year periodic fluctuations in desertification likely reflect variations in precipitation and soil moisture across the MP. Further research linking TCA, DI, TGSI, and PI values to specific desertification characteristics is recommended to establish robust thresholds and enhance assessment accuracy through field investigation.

Keywords: desertification; MODIS; desert; sand dune; sandy land; Mongolian Plateau

1 Introduction

Desertification poses severe ecological, environmental, and socio-economic threats globally, directly affecting 2.5×10 people and one-third of Earth' s surface (over 4.0×10 km^2; UNCCD, 2016a). Defined by the United Nations Convention to Combat Desertification (UNCCD) in 1994 as land degradation in arid, semi-arid, and dry sub-humid areas resulting from climatic variation and human activities, desertification manifests diversely across Asia, which contains approximately 1.7×10 km^2 of vulnerable lands. Expanding deserts in China, Mongolia, India, Iran, and Pakistan exemplify this phenomenon (UNCCD, 2016b). As Asia' s second-largest plateau, the Mongolian Plateau (MP) comprises primarily China' s Inner Mongolia Autonomous Region (IMAR, 1.18×10 km^2) and Mongolia (1.57×10 km^2; Fang et al., 2015). Approximately 90% of Mongolia consists of hyper-arid, arid, semi-arid, and dry sub-humid areas, with roughly 72% of the country vulnerable to desertification (Yu et al., 2013; Eckert et al., 2015). In IMAR, 60% of the land area falls within these aridity zones and suffers from desertification (Ci and Wu, 1997). Rapid population and livestock growth, urbanization, and mining over recent decades have intensified desertification mitigation challenges for both Chinese and Mongolian governments, creating an urgent need to understand and control desertification dynamics regarding its status, trends, and drivers. Remote sensing offers the most effective approach for monitoring and mapping these processes (Xiao et al., 2006; Albalawi and Kumar, 2013).

Traditional site-specific desertification monitoring methods struggle to capture spatial extent (Collado et al., 2002; Lam et al., 2010). Remote sensing, with its capacity for rapid, reliable data collection across vast areas, has become essential for monitoring desertification dynamics (Cui et al., 2006; Albalawi and Kumar, 2013). Vegetation and land use changes serve as the most common indicators, with vegetation change representing the most direct signal of land degradation and desertification processes (Yang et al., 2005; Xu et al., 2009). Scholars commonly employ vegetation indices such as NDVI, SAVI, MSAVI, EVI, VTCI, and OPVI for desertification assessment (Cui et al., 2006; Xu et al., 2009; Yu et al., 2013). Additional indices reflecting spatial heterogeneity—including land surface temperature (LST), albedo, LSWI, MSDI, and RUE—also contribute to assessments. In Mongolia, MODIS NDVI time series trend analysis detects vegetation change for land degradation monitoring (Eckert et al., 2015), while NDVI combined with field surveys effectively monitors steppe desertification (Sternberg et al., 2011). MODIS NDVI cross-referenced with meteorological aridity indices identified recent Gobi contraction in East Asia (Sternberg et al., 2015). MSAVI2 from SPOT-4 VEGETATION data (1998-2001) better estimated biomass and monitored degradation on Mongolian desert steppes than NDVI or EVI (Javzandulam et al., 2005). VTCI from multi-temporal Landsat-5 images predicted vegetation distribution and monitored desertification in Bulgan, Mongolia (Yu et al., 2013). Combined NDVI, MSDI, and albedo from Landsat quantitatively assessed Ordos Plateau desertification across three decades (Xu et al., 2009). TGSI, developed from field spectral measurements and laboratory grain size analysis, detected desertification in Siziwang Banner, IMAR (Xiao et al., 2006). Integrating NDVI, TGSI, and albedo from Landsat revealed an 87% difference in desertification area in central Mongolia' s Hogno Khaan reserve between 1990 and 2011 (Lamchin et al., 2016). However, Landsat MSS-derived vegetation indices achieved only ~48% accuracy for Horqin Sandy Land desertification mapping (Bremborg, 1996), and MSAVI variation proved insufficient for assessing degradation in Mongolia' s Gobi-Altai province, suggesting vegetation greenness alone inadequately indicates land degradation (Vova et al., 2015).

Land use and land cover change (LUCC) represents a primary ecosystem degradation driver and key desertification research topic. SPOT VEGETATION time-series produced land cover maps detecting sparse vegetation as desertification risk indicators in North China (Huang and Siegert, 2006). GIS-based approaches combined land cover patterns, Landsat NDVI, and wind direction for desertification monitoring in Yulin, Northwest China (Zhang et al., 2008). Mu Us Sandy Land degradation status, rates, and causes were analyzed using 1950s–1990s land cover change (Wu and Ci, 2002), while change vector analysis of NDVI and albedo examined LUCC dynamics associated with degradation (Karnieli et al., 2014). However, vegetation monitoring alone cannot fully quantify desertification (Kawamura and Akiyama, 2010; Albalawi and Kumar, 2013), and some scholars critique vegetation-based detection (Shafie et al., 2012). In the Gobi desert, NDVI requires ground verification due to limited vegetation cover reducing precision (Lam et al., 2010; Sternberg et al., 2011; Zhao et al., 2015). Field data collection and ground investigation remain infeasible across the vast, remote MP (Sternberg, 2012).

Sandy desertification constitutes a primary land degradation form in the MP, particularly in northern China (Elhadi et al., 2009; UNCCD, 2016b). Deserts cover 14.3% of Mongolia (Yang et al., 2004) and 40.0% of IMAR (John et al., 2008), expanding steadily since the 1950s (Eltahir et al., 2009). Including sand dune encroachment in monitoring would significantly improve risk prediction accuracy (Lam et al., 2010; El-Magd et al., 2013). Multi-temporal satellite image comparison through visual interpretation, spectral brightness differences, albedo, temperature, image subtraction, and classification effectively monitors dune encroachment (Hu et al., 2002; Yao et al., 2007; Hereher, 2010; Lam et al., 2010; Hermas et al., 2012; Hugenholtz et al., 2012). However, tasseled cap transformation (TCT) components—brightness (TCB), greenness (TCG), and wetness (TCW)—synthesize spectral information into physically meaningful components and outperform discrete bands or indices like NDVI, MSAVI, and NDMI for land cover characterization (Jin and Sader, 2005; Lozano et al., 2007; Powell et al., 2010; Czerwinski et al., 2014; Liu et al., 2016).

Recent applications combine TCT indices like DI and TCA for forest disturbance detection and land cover change analysis (Masek et al., 2008; Powell et al., 2010; Gómez et al., 2011; Baumann et al., 2014). DI, a linear combination of normalized TCB, TCG, and TCW, highlights unvegetated signatures while reducing sensitivity to solar geometry, BRDF effects, and phenological variability (Masek et al., 2008). Disturbed areas exhibit higher DI values, and DI=3.0 provides optimal disturbance mapping across forest biomes (Baumann et al., 2014). TCA condenses TCG/TCB ratio information into a single value representing vegetated versus non-vegetated proportions, with dense vegetation showing high TCA values and bare soil showing negative values (Gómez et al., 2011). PI, derived from TCA temporal changes, detects continuous subtle changes like natural succession (Gómez et al., 2011). However, TCT applications for sand dune encroachment remain limited.

This study aims to characterize desertification processes using TGSI integrated with three TCT-derived indices and assess 2000–2015 desertification changes and trends across the MP through decision tree (DT) classification of dunes and sandy lands. Thirteen sand dune and sandy land sites were selected to represent MP-wide desertification processes.

2.1 Study Area

The MP, located in temperate Asia' s hinterland, supports a population of ~2.8×10 (0.3×10 in Mongolia and 2.5×10 in IMAR in 2015; Fang et al., 2015). Steppe vegetation dominates, including meadows and typical/desert steppes (Zhao et al., 2015). The hyper-continental climate exhibits highest mean annual temperatures in desert steppe (1.2°C in Mongolia, 5.3°C in IMAR) and lowest in desert steppe (–1.1°C in Mongolia, 1.9°C in IMAR; Fang et al., 2015; Zhao et al., 2015). Prevailing winds blow from the northwest and west year-round (Yao et al., 2007; Li, 2011; Karnieli et al., 2014; Lamchin et al., 2016). Major deserts include Badain Jaran, Tengger, Ulan Buh, and Hobq, while sandy lands include Mu Us, Otindag, Horqin, and Hulun Buir (Zha and Gao, 1997; Kawamura and Akiyama, 2010). The vast Gobi desert region spans northern IMAR and southern Mongolia.

This study examined: Khar Nuur Sand Dune (Site 1), Ereen Nuur Sand Dune (Site 2), Tsagan Nuur Sand Dune (Site 3), Khongoryn Els Sand Dune (Site 4), Khar Khorin and Bayan Gobi (Site 5), Badain Jaran Desert (Site 6), Tengger Desert (Site 7), Ulan Buh Desert (Site 8), Hobq Desert (Site 9), Mu Us Sandy Land (Site 10), Otindag Sandy Land (Site 11), Horqin Sandy Land (Site 12), and Hulun Buir Sandy Land (Site 13) [Figure 1: see original paper].

2.2 Data and Methodology

MODIS Nadir BRDF-Adjusted Reflectance (NBAR) data were obtained from the United States Geological Survey (USGS). NBAR data minimize geometry-related artifacts compared to raw reflectance, offer seven spectral bands comparable to Landsat TM, and provide an optimal basis for tasseled cap extension (Lobser and Cohen, 2007). Collection 5 MODIS MCD43A4 16-day NBAR products at 500 m spatial resolution for August (2000–2015) were downloaded from GloVis (http://glovis.usgs.gov/). After mosaicking, projection transformation, and cloud removal, a cloud-free dataset was compiled for 2000–2015.

TCB, TCG, and TCW were derived from MODIS MCD43A4 data using tasseled cap coefficients from Lobser and Cohen (2007).

TGSI, developed from field spectral reflectance measurements and laboratory topsoil grain composition analysis, correlates positively with fine sand content (R^2=0.7387; Xiao et al., 2006). Based on Landsat TM/ETM+ results (Xiao et al., 2006), TGSI values near zero correspond to vegetation and water bodies (sometimes negative), while fine sand areas (i.e., deserts) exhibit values around 0.20. TGSI is estimated using Equation 1, where Rb1, Gb4, and Bb3 represent the red, green, and blue bands of MCD43A4 data, respectively.

2.3 Classification of Sand Dunes and Sandy Lands

Decision tree (DT) classification, employing a flowchart-like multistage process based on splitting thresholds, assessed desertification status (Xu et al., 2009; Lamchin et al., 2016). Without ground truth data, statistical criteria combined with expert interpretation of high-resolution Google Earth images were used to detect sand dunes and sandy lands using TCA, DI, and TGSI variables [Figure 2: see original paper]. Desertification was classified into six grades: none (zero desertification), low sandy land (LSL, low desertification), coarse sandy land (CSL, medium desertification), fine sandy land (FSL, high desertification), coarse sand dune (CSD, severe desertification), and fine sand dune (FSD, severe desertification). Post-classification, rectangular buffer masks constrained calculations and analysis to the thirteen study sites.

2.4 Accuracy Assessment

Detailed accuracy assessment was precluded by insufficient field data. Informal evaluation compared DT classifications against visual interpretation of MCD43A4 images, field photographs, and corresponding Landsat and high-resolution imagery, plus previous research results (Hu et al., 2002; Xu et al., 2009; Guo et al., 2010; Li, 2011; Zhang et al., 2012; Duan et al., 2014; Lamchin et al., 2016; Wang et al., 2017). With limited ground truth verification, 14,593 random sample pixels (1% of pixels across thirteen sites) were generated from DT classification results using random sampling. After overlaying these samples on contemporaneous Landsat TM/ETM+ and OLI images covering all sites, correct and incorrect classifications were determined through visual interpretation with Google Earth high-resolution imagery. A confusion matrix calculated producer accuracy, user accuracy, overall accuracy, and Kappa coefficient for desertification versus non-desertification.

3.1 TCA, DI and TGSI

Figure 3 illustrates TCA, DI, and TGSI dynamics across the thirteen sites from 2000-2015.

Site 1 exhibited decreasing mean TCA during 2000-2002, 2004-2008, and 2010-2012, with increasing mean DI during 2004-2008 and 2010-2012. TGSI values ranged 0.203-0.229. **Site 2** experienced more extensive desertification, showing decreasing TCA during 2000-2002, 2005-2007, and 2010-2012, and increasing DI during 2007-2009 and 2010-2012, indicating fluctuating surface conditions.

TGSI values ranged 0.217-0.232, revealing a fluctuating increase in fine sand proportion from 2000-2006 followed by a decrease through 2015.

Site 3 displayed negative average TCA in eleven of sixteen years, indicating persistently low vegetation-to-non-vegetation ratios, particularly from 2004-2010 when all values were negative, signifying sustained desertification. DI increased from 2003-2005 and 2011-2013, but decreased during 2001-2003, 2005-2007, and 2013-2015. TGSI values ranged 0.213-0.225. **Site 4** showed negative average TCA in fifteen of sixteen years, with values near -0.05 in 2001, 2002, 2005, 2009, and 2010 indicating extremely low vegetation proportions. Mean DI remained near 1.0 throughout, suggesting low dune/sandy land presence. TGSI showed slight increases during 2000-2003 and 2010-2012, and a decrease from 2003-2005.

Site 5 maintained positive average TCA throughout, as dunes and sandy lands comprised small landscape portions. TCA decreased during 2000-2002 and 2012-2014, but increased during 2004-2006, 2007-2009, and 2010-2012. DI was negative in twelve of sixteen years, indicating low dune/sandy land proportions. TGSI values (0.200-0.226) increased slightly during 2002-2004 and 2006-2008, and decreased during 2004-2006 and 2010-2013.

Site 6 (Badain Jaran Desert) showed negative average TCA throughout 2000-2015, indicating high non-vegetated proportions. Values near -0.05 with low standard deviations suggested relative landscape stabilization. Highly positive DI indicated high temperature, low moisture, and sparse vegetation. TGSI ranged 0.215-0.235, with bimodal distributions indicating size-sorted fine and coarse grains dominated by coarse particles. **Site 7** (Tengger Desert) exhibited negative average TCA except in 2012, showing high non-vegetated proportions. Highly positive DI indicated high temperature, low moisture, and sparse vegetation. TGSI values (0.241-0.260) were highest among all sites, indicating abundant fine sands.

Site 8 (Ulan Buh Desert) showed mean TCA below 0.01, indicating high non-vegetated proportions. Highly positive DI persisted throughout, signaling high temperature, low moisture, and sparse vegetation. TGSI values (0.217-0.237) resembled Badain Jaran more than Tengger Desert. **Site 9** (Hobq Desert) had mean TCA above 0.01, as dunes and sandy lands occupied small landscape portions. Positive average DI in twelve of sixteen years indicated relatively high temperature and low moisture. TGSI ranged 0.207-0.220, with bimodal distributions showing size-sorted grains dominated by coarse particles.

Site 10 (Mu Us Sandy Land) showed TCA increasing from 2005-2008 but decreasing during 2008-2011 and 2012-2015, indicating periodic vegetation proportion fluctuations. Negative DI throughout suggested relatively high vegetation cover. TGSI ranged 0.202-0.235. **Site 11** (Otindag Sandy Land) maintained average TCA above 0.15, indicating relatively high vegetation cover. TCA increased during 2001-2004 and 2009-2012, but decreased from 2012-2014. Low positive DI in fifteen of sixteen years likely reflected water bodies and sparse vegetation. TGSI values (0.180-0.218) increased during 2004-2007, 2008-2010, and 2011-2014, showing periodic fine-grained particle proportion increases.

Site 12 (Horqin Sandy Land) had minimum mean TCA in 2009, but values exceeded 0.18 overall, indicating relatively high vegetation cover. TCA increased from 2009-2013 but decreased during 2001-2003, 2004-2007, and 2013-2015. Low negative DI in seven of sixteen years likely resulted from sparse water bodies and vegetation. TGSI ranged 0.192-0.213. **Site 13** (Hulun Buir Sandy Land) showed average TCA above 0.12 throughout, indicating relatively high vegetation cover. Negative DI values likely reflected sparse water bodies and vegetation. TGSI values (0.167-0.203) indicated higher coarse sand content than in Horqin Sandy Land.

Across all thirteen sites, mean TGSI showed slight fluctuations but no significant 2000-2015 trend, indicating relative topsoil grain size stabilization across the MP.

3.2 Desertification Change Processes—PI

Average PI values reveal global change status and trends through consecutive date evaluations (Gómez et al., 2011). PI distributions were typically unimodal. Five PI groups were established: stable (near-zero PI, no change), slow increase (-0.05 to 0.00, slow desertification), slow decrease (0.00 to 0.05, slow restoration), fast increase (<-0.05, rapid desertification), and fast decrease (>0.05, rapid restoration). Thresholds were determined from mean ± two standard deviations.

Figure 4 shows PI dynamics across the thirteen sites from 2000-2015.

Sites 1-5: Fast increase/decrease group pixels were infrequent, while slow increase/decrease groups were common. **Site 1** showed negative average PI in nine of sixteen years, particularly 2004-2008, indicating slow desertification. PI values near zero in 2004, 2005, 2007, 2008, and 2012 indicated relative stability. **Site 2** had negative average PI in ten of sixteen years, with 2004-2008 showing desertification. Significant restoration occurred in 2002 and 2010. Near-zero values in 2005, 2007, 2008, 2012, 2013, and 2014 indicated stability.

Site 3 showed negative average PI in eight of sixteen years. Positive values during 2009-2011 indicated slow restoration, while negative 2012-2014 values indicated slow desertification. Near-zero values in 2003, 2005, 2008, 2009, 2012, 2013, and 2014 indicated stability. **Site 4** had negative average PI in nine of sixteen years, with 2007-2009 showing desertification. Near-zero values in 2003, 2005, 2007, 2012, 2013, and 2014 indicated stability. **Site 5** showed positive average PI in ten of sixteen years, with 2008-2012 indicating restoration. Near-zero values in 2007, 2009, and 2010 indicated stability, while values near -0.05 in 2001 and 2013 indicated rapid desertification, and values near 0.05 in 2005 and 2011 indicated rapid restoration.

Sites 6-13: Slow increase/decrease groups dominated. **Site 6** (Badain Jaran Desert) showed positive average PI in nine of sixteen years, indicating slow restoration, but near-zero values confirmed relative stability. **Site 7** (Tengger Desert) had negative average PI in nine of sixteen years, indicating slow desertification, but near-zero values showed relative stability. **Site 8** (Ulan Buh Desert) exhibited negative average PI in ten of sixteen years, indicating slow desertification, but near-zero values confirmed stability. **Site 9** showed negative average PI in eight of sixteen years, indicating slow desertification, with stability in 2003, 2005, and 2008. **Site 10** had negative average PI in nine of sixteen years, indicating slow desertification, with stability during 2003-2005 and 2007-2010. **Site 11** showed negative average PI in nine of sixteen years, indicating slow desertification, with stability in 2001 and 2005-2007. **Site 12** had positive average PI in nine of sixteen years, indicating slow restoration. **Site 13** exhibited positive average PI in ten of sixteen years, indicating slow restoration, with stability in 2006, 2007, 2009, 2011, and 2012.

3.3 Assessment of Desertification

The 500 m pixels of MCD43A4 products represent mixed land cover classes, and objects like Gobi desert and barren lands with similar TCA, DI, and TGSI signatures can create errors. Study site buffers partially reduced DT classification errors. Contemporaneous Landsat TM/ETM+ (fifty-two TM and five ETM+ images) and OLI (nineteen images) covered all thirteen sites, enabling DT classification evaluation. As Table 1 shows, overall Kappa coefficients and accuracies were 0.7759 and 91.71% (2000), 0.7659 and 90.71% (2005), 0.7737 and 91.71% (2010), and 0.7649 and 90.44% (2015), reflecting strong classification performance. TGSI was critical for distinguishing CSL, FSL, CSD, and FSD classes. Comparison with grain size analyses from the Badain Jaran-Tengger Deserts (Li, 2011) confirmed TGSI as a reliable surface deposit grain size indicator, lending credibility to our desertification classification. Additionally, our DT-derived desertification maps aligned with previous maps for Mu Us Sandy Land (Xu et al., 2009; Wang et al., 2017), Horqin Sandy Land (Hu et al., 2002; Zhang et al., 2012; Duan et al., 2014), Hulun Buir Sandy Land (Guo et al., 2010), and Khar Khorin and Bayan Gobi (Lamchin et al., 2016), supporting class reliability and regional-scale assessment applicability.

Due to space constraints, we present only the 2015 desertification map for all thirteen sites [Figure 5: see original paper] and annual changes for Site 3' s main sand dune from 2000-2015 [Figure 6: see original paper].

From 2000-2015, most sites showed fluctuating rather than monotonic desertification trends. Peak desertification areas occurred in 2012 for Sites 1 (20.6%), 2 (34.0%), 3 (51.1%), 6 (65.7%), and 7 (68.1%); in 2001 for Site 4 (18.3%); 2002 for Site 5 (5.6%); 2003 for Sites 8 (55.2%) and 9 (15.6%); 2000 for Site 10 (13.4%); 2005 for Site 11 (21.6%); 2009 for Site 12 (20.0%); and 2004 for Site 13 (3.8%).

Figure 6 shows Site 3' s main sand dune annual changes. Maximum desertification area in 2001 reflected severe drought. Total desertification and coarse sand dune areas increased from 2003-2005, but decreased during 2001-2003, 2005-2007, 2008-2011, and 2012-2015, with an overall slowdown from 2000-2015 [Figure 6a: see original paper]. Low sandy land, fine sandy land, and fine sand dune areas showed fluctuating increases [Figure 6b: see original paper], with southwest and northeast portions experiencing variable changes.

For sand dunes and deserts, coarse and fine sand dunes dominated desertified areas, peaking in 2008 (6.2%) and 2013 (1.5%) at Site 1; 2009 (20.4%) and 2013 (3.3%) at Site 2; 2008 (42.4%) and 2005 (0.9%) at Site 3; 2001 (15.4% and 2.6%) at Site 4; 2003 (54.2%) and 2012 (8.7%) at Site 6; 2007 (41.9%) and 2006 (26.1%) at Site 7; 2003 (51.3%) and 2013 (12.8%) at Site 8; and 2001 (8.2%) and 2003 (2.2%) at Site 9. For sandy lands, low, coarse, and fine sandy lands dominated. Low and fine sandy land areas peaked in 2002 (5.3%) and 2004 (1.7%) at Site 5; 2000 (7.7% and 3.8%) at Site 10; and 2014 (7.8%) and 2004 (1.7%) at Site 11. Low and coarse sandy land areas peaked in 2009 (14.6%) and 2000 (5.7%) at Site 12, and in 2004 (3.4% and 0.3%) at Site 13.

4 Discussion

TCA effectively discriminates sand dunes, sandy lands, and vegetation. Generally, sand dune TCA values fall below zero, while sandy lands range 0.0–0.1, reflecting better vegetation cover. Minimum mean TCA values occurred in 2002 for Sites 1, 5, and 6; 2009 for Sites 2, 11, and 12; and 2001 for Sites 3, 4, 7, 8, 9, 10, and 13, corresponding to severe drought and low soil moisture years (Dorjsuren et al., 2016; Lamchin et al., 2016). These inter-site differences likely reflect varying climate change rates.

DI, derived from TCB, TCG, and TCW, reduces moisture and vegetation effects simultaneously, sometimes outperforming TCA for dune identification. TGSI reports surface grain size within defined areas. This study classified TGSI >0.21 as sand dune or sandy land, differing from Landsat-based studies in Mongolia and Inner Mongolia (Xiao et al., 2006; Lamchin et al., 2016), likely due to sensor differences despite MCD43A4' s Landsat TM-comparable spectral bands. TGSI better characterizes dune and sandy land structures (coarse/fine dunes and lands) than DI, which is crucial for studying dune movement and sand shift, though it sometimes inadequately differentiates sandy lands from background.

The Tengger Desert exhibited higher DI and TGSI than other sites, indicating a brighter, finer surface. Integrating TCA, DI, and TGSI advantages improved desertification identification and assessment.

PI effectively captures desertification change trends and processes missed by bi-temporal approaches. Maximum mean PI did not correspond to maximum precipitation years, suggesting restoration may reach environmental limits before precipitation peaks. Over sixteen years, Badain Jaran, Tengger, and Ulan Buh deserts showed near-zero mean PI, indicating stability. Negative mean PI at Sites 1, 2, 3, 4, 9, 10, and 11 for over half the study period indicated slow desertification increase, while positive values at Sites 5, 12, and 13 indicated slow decrease. While permanent versus seasonal desertification remains undetermined (Sternberg et al., 2011; Eckert et al., 2015), our study identified parallel climate variability and desertification fluctuations, showing three-to-four-year periodic changes rather than continuous trends, likely reflecting precipitation, soil moisture, and vegetation restoration project variations across the MP (Sternberg et al., 2011, 2015; Dorjsuren et al., 2016; Huang, 2017; Yu et al., 2017). Horqin Sandy Land particularly showed random alternations between slow fluctuating increase and decrease, reflecting local ecological restoration project impacts (Zhang et al., 2012).

For Khar Nuur, Ereen Nuur, Tsagan Nuur, Khongoryn Els, Badain Jaran, Tengger, Ulan Buh, and Hobq, fine sand dunes concentrated in east and southeast portions, indicating downwind fine sand transport. Our finding that fine sand dunes dominated the Tengger Desert aligns with Badain Jaran-Tengger deposit grain size studies (Li, 2011), supporting our DT classification credibility. Coarse sandy land dominated Horqin Sandy Land. Sandy lands around dunes/deserts contained finer particles than coarse sandy lands, as Sites 1 and 12 comparisons demonstrate west-east MP topsoil grain size differences. Future research should explore these patterns further.

5 Conclusions

Desertification is a complex climate- and anthropogenically-driven process. This study monitored 2000–2015 MP desertification changes across thirteen sand dune and sandy land sites using MODIS MCD43A4 data. Despite lacking ground truth for detailed accuracy assessment, visual interpretation, Google Earth high-resolution imagery, and previous research confirmed DT classification suitability for regional-scale assessment.

TCA proved valuable for assessing dunes, sandy lands, and vegetation. DI sometimes outperformed TCA for dune-background differentiation. TGSI effectively described dune and sandy land structures (coarse/fine dunes and lands), essential for studying dune movement and sand shift. PI provided trend and process insights missed by bi-temporal approaches. Integrating TCA, DI, TGSI, and PI advantages improved desertification identification and assessment.

Over sixteen years, Badain Jaran, Tengger, and Ulan Buh deserts remained relatively stable. Khar Nuur, Ereen Nuur, Tsagan Nuur, Khongoryn Els, and Hobq deserts, plus Mu Us and Otindag sandy lands, showed gradual desertification increase, while Bayan Gobi, Horqin, and Hulun Buir sandy lands showed gradual decrease.

Limitations remain, including mixed pixel effects and threshold selection. While relative TCA, DI, TGSI, and PI change evaluation required no calibration and MODIS MCD43A4 provided nadir-standardized reflectance, future work should examine normalization among these indices. Further research linking TCA, DI, TGSI, and PI values to specific desertification characteristics is recommended for threshold optimization and accuracy improvement.

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