Spatio-temporal dynamics of desertification in China from 1970 to 2019: A meta-analysis postprint

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Abstract

Desertification is a global crucial ecological and environmental issue, and China is among the countries most seriously affected by desertification. In recent decades, numerous independent studies on desertification dynamics have been carried out using remote sensing technology, but there has been a lack of systematic research on desertification trends in China. This study employed the meta-analysis to integrate the findings of 140 published research cases and examined the dynamics of desertification in the eight major deserts, four major sandy lands, and their surrounding areas in China from 1970 to 2019, with a comparative analysis of differences between the eastern (including the Mu Us Sandy Land, the Otindag Sandy Land, the Hulunbuir Sandy Land, the Horqin Sandy Land, and the Hobq Desert) and western (including the Taklimakan Desert, the Gurbantunggut Desert, the Kumtagh Desert, the Ulan Buh Desert, the Qaidam Basin Desert, the Badain Jaran Desert, and the Tengger Desert) regions. The results revealed that from 1970 to 2019, desertification first expanded and then reversed in the whole region. Specifically, desertification expanded from 1980 to 1999 and reversed after 2000. The desertification trend exhibited distinct spatio-temporal variations between the eastern and western regions. From 1970 to 2019, the western region experienced relatively minor changes in desertified land area compared to the eastern region. In the context of global climate change, beneficial climatic conditions and ecological construction projects played a crucial role in reversing desertification. These findings provide valuable insights for understanding the development patterns of desertification in the most representative deserts and sandy lands in China and formulating effective desertification control strategies.

Full Text

Preamble

Spatio-temporal Dynamics of Desertification in China from 1970 to 2019: A Meta-analysis

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Abstract

Desertification represents a critical global ecological and environmental challenge, with China ranking among the most severely affected nations worldwide. Over recent decades, numerous independent studies have investigated desertification dynamics using remote sensing technology, yet systematic research on nationwide trends remains lacking. This study employed meta-analysis to integrate findings from 140 published research cases, examining desertification dynamics across China's eight major deserts, four major sandy lands, and their surrounding areas from 1970 to 2019. The analysis compared differences between eastern regions (Mu Us Sandy Land, Otindag Sandy Land, Hulunbuir Sandy Land, Horqin Sandy Land, and Hobq Desert) and western regions (Taklimakan Desert, Gurbantunggut Desert, Kumtagh Desert, Ulan Buh Desert, Qaidam Basin Desert, Badain Jaran Desert, and Tengger Desert). Results revealed that desertification initially expanded then reversed across the entire study area, with expansion occurring from 1980 to 1999 and reversal after 2000. Distinct spatio-temporal variations emerged between eastern and western regions, with the western region experiencing relatively minor changes in desertified land area compared to the eastern region. In the context of global climate change, favorable climatic conditions combined with ecological restoration projects played a crucial role in reversing desertification. These findings provide valuable insights for understanding development patterns in China' s most representative deserts and sandy lands and for formulating effective desertification control strategies.

Keywords: desertification dynamics; sandy land; desert; climate change; human activities; meta-analysis

1 Introduction

Desertification is land degradation occurring primarily in arid, semi-arid, and dry sub-humid areas, collectively known as drylands. It results from multiple factors, including climate change and human activities (United Nations General Assembly, 1994). All United Nations member states adopted the 2030 Agenda for Sustainable Development, which establishes 17 Sustainable Development Goals (SDGs) (United Nations Sustainable Development Summit, 2015). Among these, SDG 15.3 focuses specifically on combating desertification and land degradation, underscoring its status as a global concern. China ranks among the world's most severely desertification-affected countries, with national surveys indicating that by 2019, desertified land covered 257.37\$×10^{4}\$ km^2, representing approximately 26.81% of China' s terrestrial area (Zan et al., 2023).

Climate change significantly influences desertification through its effects on regional water availability, soil moisture, and vegetation cover variations (Huang et al., 2009; Costa and Soares, 2012). Increased precipitation benefits vegetation restoration and promotes desertified land recovery, whereas drought can cause vegetation degradation and desertification expansion. Human activities also substantially impact desertification processes. Ecological engineering projects in desertification areas—such as vegetation enclosure for restoration, aerial seeding for sand control, and converting grazing land back to grassland—can restore desertified land (Li et al., 2021). Conversely, overgrazing, overcultivation, and excessive groundwater use can drive desertification expansion (Wu and Ci, 1998; Huang et al., 2020). Understanding desertification dynamics is therefore crucial for scientific land-use decision-making and effective desertification control (Wu and Ci, 2002).

Traditional desertification studies and monitoring relied on field surveys, which proved labor-intensive, costly, and limited in temporal and spatial scope, making large-scale surveys difficult. Remote sensing technology, emerging in the mid-20th century, overcame many limitations of traditional surveys through its macroscopic, multi-temporal, multi-band, comprehensive, and cost-effective characteristics (Xiu et al., 2024). Various monitoring and evaluation methods have been developed, establishing a foundation for desertification research in northern China. The 1972 launch of Earth observation satellites initiated a new era of global observation and vegetation studies (Zeng et al., 2022). Over the past 40 years, remote sensing technology advancement has enabled desert monitoring at global, continental, and regional scales. Satellite data from NOAA (National Oceanic and Atmospheric Administration) (Helldén and Tottrup, 2008), MODIS (Moderate Resolution Imaging Spectroradiometer) (Sun et al., 2015), Landsat (Li et al., 2013), SPOT (Systeme Probatoire d' Observation de la Terre) (Huang and Siegert, 2006), CBERS (China-Brazil Earth Resources Satellite) (Liu et al., 2008), and Sentinel (Lamqadem et al., 2018) have demonstrated remote sensing' s potential for desertification monitoring (Wang et al., 2022).

Recent years have witnessed comprehensive application of multi-band, multispectrum, multi-angle, and multi-polarization remote sensing to improve desertification monitoring and assessment (Feng et al., 2022). For example, unmanned aerial vehicle data serve as auxiliary monitoring data (Zhao et al., 2018), while radar remote sensing compensates for conventional satellites' limitations under adverse weather conditions (Kim et al., 2021). Desertification information extraction from remote sensing data has evolved from human-computer interactive visual interpretation to automatic classification and machine learning methods (Fathizad et al., 2018; Fan et al., 2020; Pi et al., 2020). Additionally, indicator-based assessment systems have gradually improved (Tucker, 1979; Piao et al., 2005; Fensholt et al., 2012; Lamchin et al., 2016), developing structures with single and multiple assessment indicators (Sommer et al., 2011). Nevertheless, variations in remote sensing data, information extraction techniques, and assessment indicators may contribute to discrepancies in research results. With rapid advances in artificial intelligence, big data, and cloud computing, diverse methods and data sources are urgently needed to analyze desertification dynamics and trends in China.

Since the 1980s, desertification dynamics research in China has received widespread attention from academia and government (Fullen and Mitchell, 1994; Lu et al., 2019; Duan et al., 2021). Remote sensing provides multi-scale, multi-temporal, multi-band spatial data for long time series, enabling long-term, continuous regional-scale research (Xiu et al., 2024). Recent technological developments have greatly advanced desertification dynamics studies. While numerous independent studies have examined desertification dynamics across China (Wu et al., 2013; Guo et al., 2017; Duan et al., 2021), systematic analysis of these results remains lacking. Meta-analysis has become a valid tool for accurate quantitative assessment and evidence synthesis on environmental issues (Hillebrand, 2004; Gurevitch et al., 2018; Wang et al., 2021). This study applied meta-analysis to integrate and analyze desertification dynamics across China' s most representative deserts and sandy lands since 1970, aiming to: (1) construct an overview of peer-reviewed literature on desertification dynamics in China, and (2) quantify temporal trends and spatial differences in desertification. The results will provide references and support for desertification control measures.

2.1 Study Area

China' s drylands and desertification-prone areas are located primarily in the northern region, covering approximately 4.52$×10^{6}$ km^2 (about 47.10% of China' s terrestrial area) (Wu et al., 2007). China' s eight major deserts (Taklimakan, Gurbantunggut, Kumtagh, Ulan Buh, Hobq, Qaidam Basin, Badain Jaran, and Tengger) and four sandy lands (Mu Us, Otindag, Hulunbuir, and Horqin) are distributed throughout these drylands (35°–50°N, 76°–125°E; Fig. 1 [Figure 1: see original paper]). These deserts, sandy lands, and surrounding areas represent China' s most severely desertified regions. The climate is typical temperate continental, with annual precipitation generally below 400 mm, concentrated mainly in summer. Vegetation coverage is low, surface sediments are loose and wind-erodible, and strong winds and sandstorms frequently occur in spring.

Chinese desertification regions exhibit two distinct types with different climate characteristics and driving factors. The first type includes the agro-pastoral ecotone in northern China' s semi-arid and dry sub-humid areas, where the four major sandy lands are distributed (primarily in central and eastern Inner Mongolia Autonomous Region, Shaanxi Province, and Hebei Province). Desertification here mainly results from human activities such as overcultivation and overgrazing. The second type comprises oasis areas along or downstream of inland rivers in northern China' s arid and hyper-arid regions, where the eight major deserts are distributed (primarily in Xinjiang Uygur Autonomous Region, western Inner Mongolia Autonomous Region, Gansu Province, and Qinghai Province). Desertification in these regions primarily stems from water resource overuse and excessive groundwater extraction.

These eight deserts and four sandy lands, along with their surrounding regions, represent China' s most severely desertified and most representative areas. This study selected these regions for meta-analysis of spatio-temporal desertification patterns and trends since the 1970s. To facilitate spatial difference analysis and comparison, areas containing the four sandy lands and Hobq Desert were designated as the eastern region, while areas containing the other seven deserts were designated as the western region. The Hobq Desert lies in a transitional zone between arid and semi-arid areas, with desertification characteristics similar to the adjacent Mu Us Sandy Land; both are located on the Ordos Plateau, leading to its inclusion in the eastern region.

2.2 Data Collection and Extraction

We searched peer-reviewed literature using Web of Science (https://www.webofscience.com) and China National Knowledge Infrastructure (https://www.cnki.net). Retrieval employed keyword terms related to the eight deserts and four sandy lands: (1) "Taklimakan Desert" OR "Gurbantunggut Desert" OR "Badain Jaran Desert" OR "Tengger Desert" OR "Qaidam Basin Desert" OR "Kumtagh Desert" OR "Hobq Desert" OR "Ulan Buh Desert" OR "Mu Us Sandy Land" OR "Mu Us Desert" OR "Horqin Sandy Land" OR "Horqin Desert" OR "Otindag Sandy Land" OR "Otindag Desert" OR "Hulunbuir Sandy Land" OR "Hulunbuir Desert" ; and (2) "desertification" OR "landscape" OR "degradation" OR "monitor" *OR* " *remote sens*" . Publication year was unrestricted, yielding 8,131 references.

The literature search was conducted in March 2025. Following Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines, we applied inclusion and exclusion criteria: (1) remote sensing-based desertification monitoring with clear status reports; (2) desertification monitoring or assessment within specific timeframes; (3) clearly indicated desertification degree;

and (4) provision of desertification monitoring data showing area and degree of land degradation. Duplicate literature was removed using NoteExpress software (version 3.4.0.8779). After duplicate removal, 6,743 references remained. Title, abstract, and full-text screening yielded 140 valid articles (each serving as one research case), comprising 99 journal articles, 8 doctoral dissertations, 27 master' s theses, and 6 conference papers. The detailed PRISMA process and results appear in Figure 2 [Figure 2: see original paper].

From each research case, we extracted study area information, study period, remote sensing data used (types and sensors), desertification assessment indicators, and desertification dynamics data. Desertification data displayed in figures were extracted using PlotDigitizer software (version 2.6.9) (https://plotdigitizer.com/). General characteristics recorded included title, author and affiliation, publication name, and year. We designed a database based on the 140 articles, with identification fields, study area, and desertification dynamics data. Articles containing multiple research cases were recorded separately by research area.

Desertification classification systems varied across research cases. Some categorized desertified land into fixed, semi-fixed, and shifting sandy lands to represent different degradation degrees; others used three levels (light, moderate, severe); while some further subdivided severe into severe and extremely severe, creating a four-level system (light, moderate, severe, extremely severe). Analysis revealed that despite inconsistent classification systems and standards, the patterns and trends of desertification dynamics were consistent across research results. This study reclassified raw data into three levels: light, moderate, and severe (State Forestry Administration, 2013). Notably, severe and extremely severe classifications were merged into a single severe level. Fixed, semi-fixed, and shifting sandy lands were classified as light, moderate, and severe desertification, respectively.

2.3 Overview of Research Cases and Monitoring Period Determination

The earliest article in the database was published in 1987, focusing on Hulunbuir Sandy Land (Fan and Zhao, 1987). Publications were relatively few in the 1980s and 1990s, with the majority appearing after 2003 (Fig. 3a [Figure 3: see original paper]). The 2000s saw substantial literature publication (n=130), primarily focusing on the four major sandy lands and Hobq Desert in the eastern region, indicating recent widespread attention to desertification and remote sensing technology' s important role in promoting dynamics research. After 2011, research on western region desertification dynamics increased.

Approximately 19.29% of database literature came from the China Master' s Theses Full-text Database (n=27), 10.71% from the Journal of Desert Research (n=15), 5.71% from the China Doctoral Dissertations Full-text Database (n=8), 4.29% from the Journal of Arid Land Resources and Environment (n=6), and 4.29% from the Conference Proceedings Database (n=6). Eastern region research cases outnumbered western region cases by approximately 6.1 times (Fig. 3a).

All research cases utilized remote sensing data for desertification monitoring and assessment (Fig. 3b). Optical remote sensing data were most common, including SPOT from CNES (Centre National d' etudes Spatiales), NOAA, MODIS, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) from EOS (Earth Observation System), Landsat from NASA (National Aeronautics and Space Administration), and CBERS. Landsat series data were the most frequently used.

The 140 research cases employed five types of desertification evaluation indicators: vegetation indices (NDVI (Normalized Difference Vegetation Index), SAVI (Soil-Adjusted Vegetation Index), MSAVI (Modified Soil-Adjusted Vegetation Index), etc.), surface landscape (shifting sand area/percentage, land cover type, patch density, etc.), soil (soil texture, gravel cover area/percentage, TGSI (Topsoil Grain Size Index), soil type, etc.), climate (precipitation, temperature, wind speed, etc.), and socio-economic characteristics (human activity intensity, population density, etc.). Research cases using vegetation, surface landscape, soil, climate, and socio-economic indicators numbered 130, 105, 20, 4, and 4, respectively. Single-indicator assessments comprised 61 cases (41 vegetation-only, 19 surface landscape-only, 1 soil-only), while 72 cases used two indicator types (71 using vegetation and surface landscape, 1 using vegetation and soil). Eighteen cases used $ $3 indicator types, including 14 using three types (vegetation index, surface landscape, and soil), 3 using four types, and 1 using five types (Fig. 3c). Vegetation indices and surface landscape features were the most frequently used indicators.

Study periods varied: 31 cases covered <10 years, 47 covered 10-20 years, 33 covered 21-30 years, 25 covered 31-40 years, and 4 exceeded 40 years. This study used 10-year intervals as monitoring periods. Due to limited 1950s (three cases) and 1960s (one case) data, we analyzed five monitoring periods: 1970-1979, 1980-1989, 1990-1999, 2000-2009, and 2010-2019.

For research case selection across monitoring periods, when cases didn't perfectly match these periods, the following approach was applied: using 1980-1989 as an example, we prioritized cases containing $ $2 years of monitoring data within 1980-1989. When this condition couldn' t be met, we selected cases from the late 1970s (1976-1979) and early 1990s (1990-1994). Similar selection criteria applied to other monitoring periods.

2.4 Mann-Kendall (MK) Trend Test

The MK trend test is a nonparametric method for evaluating time series data significance (Mann, 1945). It has been widely used to analyze trends in climate, hydrology, plant growth, and landscape dynamics (Wang et al., 2015a; Yao et al., 2016; Fan et al., 2017; Wang et al., 2017c; Zhao et al., 2019). To clarify recent desertification trends, we applied the MK test to individual research cases with 10-year monitoring periods, examining only cases including \$ \$3 monitoring periods. The MK trend test was conducted as follows:

The MK test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}(x_j - x_i)$$

where sign is the signum function, n is the time series length, and x_i and x_j are data values in the ith and jth years, respectively. The variance of S is:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

The standardized test statistic Z is:

$$Z = \frac{S}{\sqrt{\operatorname{Var}(S)}}$$

Positive Z values indicate significant increasing trends in desertified land area (P<0.050), while negative values indicate significant decreasing trends (P<0.050). Desertification trend significance was divided into four classes based on absolute Z values: marginally significant (1.64≤|Z|\$ $1.95, i.e., 0.050 < P\ 0.100), significant(1.96\ |Z|\ 2.31, i.e., P < 0.050), mostsignificant(2.32\ |Z|\ 2.57, i.e., P < 0.010), andextremelysignificant(|Z|$ \$2.58, i.e., P<0.001).

The MK test was performed using the 'trend' package in R version 4.2.3 (https://cran.r-project.org/web/packages/trend/index.html).

2.5 MK Mutation Test

The MK method can test time-series trends and detect change points. This study applied the MK mutation test to identify years when desertification development trends changed. Test statistic S_k, standardized statistic UF_k, and standardized statistic UB_k were calculated as follows:

The test statistic S_k is:

$$S_k = \sum_{i=1}^{k} \sum_{j=i+1}^{n} \operatorname{sign}(x_i - x_j)$$

The mean and variance of S_k are:

$$E(S_k) = \frac{k(k+1)}{4}$$

$$\operatorname{Var}(S_k) = \frac{k(k-1)(2k+5)}{72}$$

The standardized statistics are:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\text{Var}(S_k)}}$$

$$UB_k = -UF_k$$

where UF_k and UB_k analyze time series trends, clarify mutation timing, and identify mutation areas. When UF_k and UB_k curves intersect between critical lines, the intersection time indicates when mutation begins. The MK mutation test was conducted using the 'trend' package in R version 4.2.3 (https://cran.r-project.org/web/packages/trend/index.html).

2.6 Pettitt' s Test

Pettitt' s test is a nonparametric sequence mutation point test that determines mutation occurrence by examining when time series dataset means change (Pettitt, 1979). We used Pettitt' s test to examine mutation time points in desertification time series trends under assumptions of significant dataset changes. Pettitt' s test constructs the Mann-Whitney statistic U_{t,m} using:

$$U_{t,m} = \sum_{i=1}^{t} \sum_{j=t+1}^{m} \text{sign}(x_i - x_j)$$

The test statistic K_m and correlation probability P for significance testing are given by:

$$K_m = \max |U_{t,m}|$$

$$P \approx 2 \exp\left(\frac{-6K_m^2}{m^3 + m^2}\right)$$

The Pettitt' s test was conducted using the 'trend' package in R version 4.2.3 (https://cran.r-project.org/web/packages/trend/index.html).

2.7 Meta-analysis

Effect size (ES) is meta-analysis' s core indicator, representing a collective term for ES measures (Hedges and Olkin, 1985). ES choice depends on data type. For continuous variables, weighted mean difference or standardized mean difference is typically chosen, while categorical variables use relative ratio or risk ratio (Borenstein et al., 2009). As desertification degree is categorical, we selected the rate of change in area percentage of desertified land with specific degradation degrees at period end relative to beginning (RR) as the ES measure. The computational formula is:

$$RR = \frac{p_2}{p_1}$$

where p_1 and p_2 are area percentages of desertified land with a certain degradation degree at period beginning and end (%), respectively.

The approximate standard error of RR (SE_{RR}) is calculated as:

$$\mathrm{SE}_{RR} = \sqrt{\frac{1-p_1}{p_1 \cdot n_1} + \frac{1-p_2}{p_2 \cdot n_2}}$$

where n_1 and n_2 are sample sizes at period beginning and end.

The 95% confidence interval (CI) of RR (CI_{RR}) was estimated as:

$$\mathrm{CI}_{RR} = RR \pm 1.96 \times \mathrm{SE}_{RR}$$

Research cases exhibited variability across study region characteristics, remote sensing data sources, and desertification classification criteria. Therefore, we performed a random effects model in meta-analysis to address inter-case variability. The random effects model formula is:

$$\phi_J = \phi + \mu_J + \varepsilon_J$$

where ϕ_J, ϕ, and _J represent estimated ES, true ES, and error, respectively; ϕ is the gross ES mean; and _J is variation within research cases, i.e., _J~N(0, τ^2), where τ^2 is variance between research cases. Gross mean ES in the random effects model depended on case weights. Weight assignment and weighted aggregate ES are defined as:

$$w_J = \frac{1}{\tau^2 + \sigma_J^2}$$

$$\phi_{++} = \frac{\sum w_J \phi_J}{\sum w_J}$$

where w_J is the ES weight for the Jth research case in total samples; σJ^2 *is the estimated variance for research case J; and* ϕ{++} is the weighted aggregate ES. A calculated ES requires at least three research cases for validity. When ϕ*{++} with 95% CI overlaps 1, it represents invalid change; when* ϕ{++} with 95% CI does not overlap 1, it represents significant change (P<0.050). Calculating ES for each monitoring period requires $ $3 research cases. The 1970-1979 monitoring period didn’ t meet this condition, so we calculated ES for four periods: 1980-1989, 1990-1999, 2000-2009, and 2010-2019.

In meta-analysis, publication bias can be assessed using funnel plots or Egger regression. Without publication bias, funnel plots present symmetrical inverted funnel shapes; with bias, they appear asymmetric. Funnel plot symmetry evaluation is highly subjective, so we adopted Egger regression to check funnel plot symmetry. When P>0.050, no significant publication bias exists, and meta-analysis conclusions are highly reliable.

Meta-analysis was performed using the 'metafor' package in R version 4.2.3 (https://cran.r-project.org/web/packages/metafor/index.html).

3.1 Development Trends and Mutation Time Points of Desertification

Among 140 research cases, 90 cases with $ $3 monitoring periods were analyzed using the MK trend test (Fig. 4 [Figure 4: see original paper]). Results showed that positive Z values indicated significant increasing trends in desertified land area (P<0.050), while negative Z values represented significant decreasing trends (P<0.050). Development trends varied across cases: 59 showed decreasing trends and desertification reversal, 19 indicated increasing trends and expansion, and 12 represented no significant change. Among these, 12 cases showed significant decreases (P<0.050), 7 showed marginally significant decreases (P<0.100), and 1 showed a marginally significant increase (P<0.100).

The MK mutation test and Pettitt's test were applied to 20 cases with significant trends (P<0.010; Fig. 4 [Figure 4: see original paper]). Results showed that despite differing study periods, mutation time points occurred between 2000 and 2010 (Table 1). For the MK test, mutations mainly occurred between 2002 and 2005, while Pettitt' s test indicated mutations primarily between 2000 and 2005. Cases with longer study periods and reduced desertified land area showed earlier abrupt years.

3.2 Spatio-temporal Variations in Desertified Land Area Percentage

Spatial variations in desertified land area percentage occurred across the eight deserts and four sandy lands (Fig. S1). Results showed that in the eastern region, median area percentage of lightly desertified land increased (3.12%), moderately desertified land decreased slightly (-0.75%), and severely desertified land decreased (-2.21%). In the western region, lightly desertified land median area percentage increased slightly (1.41%), while moderately and severely desertified land decreased slightly (-0.17% and -1.43%, respectively; Fig. 5 [Figure 5: see original paper]). Overall, despite relatively small changes in the western region, both eastern and western regions showed increased lightly desertified land area percentages and decreased moderately and severely desertified land area percentages, indicating desertification reversal.

Considering the eight deserts, four sandy lands, and surrounding areas as a whole, area percentage of lightly desertified land first decreased then increased after 1970, while moderately desertified land decreased slightly, and severely desertified land first increased then decreased (Fig. 6a [Figure 6: see original paper]). In the western region, lightly desertified land area percentage first decreased then increased, moderately desertified land showed a decreasing trend, and severely desertified land first increased then decreased (Fig. 6b [Figure 6: see original paper]). In the eastern region, lightly desertified land area percentage first decreased then increased, moderately desertified land changed little, and severely desertified land first increased then decreased (Fig. 6c [Figure 6: see original paper]).

Compared with 1980-1999, average change rates of desertified land area percentages showed greater variation during 2000-2019, with no difference between eastern and western regions (Fig. 7 [Figure 7: see original paper]). However, comparing the four monitoring periods (1980-1989, 1990-1999, 2000-2009, and 2010-2019), average change rates varied spatially. Across all regions, lightly desertified land area percentage average change rate increased during all four periods, accelerating after 2000, with similar patterns in both eastern and western regions. Moderately desertified land area percentage average change rate showed an overall decrease through three phases: initial decrease, intermediate increase, and final decrease, with spatial variation. In the eastern region, it generally decreased: initial decrease, intermediate increase, and final decrease. In the western region, it increased through four phases: initial decrease, increase, subsequent decrease, and final increase. Severely desertified land area percentage average change rate initially increased then decreased, showing an overall declining trend with accelerated decrease since 2000, particularly in the eastern region. In summary, compared with pre-2000, post-2000 average change rates accelerated. From 1980 to 2019, lightly desertified land area percentage average change rate increased in both regions, severely desertified land decreased in both, and moderately desertified land decreased in the eastern region while increasing in the western region, resulting in an overall decrease.

3.3 Spatio-temporal Variations of ES for Desertified Land Change

Figure 8 [Figure 8: see original paper] shows ES spatio-temporal dynamics for desertified land change. During the four monitoring periods from 1980 to 2019, distinct regional change patterns emerged. From 1980 to 1989 (Fig. 8a [Figure 8: see original paper]), across all regions, lightly desertified land ES decreased, moderately desertified land ES significantly decreased (-11%; $P<0.001$), severely desertified land ES significantly increased (18%; $P<0.050$), and desertification worsened overall. In the eastern region, moderately and severely desertified land ES changes were extremely significant, with moderately desertified land ES significantly decreasing ($P<0.001$) and severely desertified land ES significantly increasing ($P<0.001$).

From 1990 to 1999 (Fig. 8b [Figure 8: see original paper]), across all regions, lightly desertified land ES remained unchanged, moderately desertified land ES decreased, severely desertified land ES increased, and desertification continued worsening. In the western region, lightly and severely desertified land ES changed significantly, with lightly desertified land ES significantly decreasing

(P<0.050) and severely desertified land ES significantly increasing (P<0.050).

From 2000 to 2009 (Fig. 8c [Figure 8: see original paper]), across all regions, lightly desertified land ES significantly increased (13%; P<0.010), moderately desertified land ES increased, and severely desertified land ES significantly decreased (-9%; P<0.010), indicating desertification reversal. In the western region, lightly desertified land ES significantly increased (P<0.050). In the eastern region, lightly and severely desertified land ES changed significantly, with lightly desertified land ES significantly increasing (P<0.050) and severely desertified land ES significantly decreasing (P<0.050).

From 2010 to 2019 (Fig. 8d [Figure 8: see original paper]), across all regions, lightly and moderately desertified land ES increased, severely desertified land ES decreased, and desertification continued reversing. In the western region, lightly and severely desertified land ES changes were very significant, with lightly desertified land ES significantly increasing (P<0.010) and severely desertified land ES significantly decreasing (P<0.010). These results indicate desertification expanded during 1980-1989 and 1990-1999, reversed during 2000-2009, and continued reversing thereafter. Egger regression results in Table S1 showed no publication bias when P>0.050, confirming sufficient result credibility.

4.1 Desertification Development Trend

Although numerous desertification studies have been conducted in China (Wu et al., 2013; Guo et al., 2017; Duan et al., 2021), comprehensive understanding of dynamics and development trends remains lacking. This study collected published research cases on eight major deserts, four major sandy lands, and surrounding areas, performing meta-analysis on desertification dynamics from 1970 to 2019, providing new insights. Desertification expanded before 2000 and reversed afterward. Lightly desertified land area percentage first decreased then increased, moderately desertified land decreased slightly, and severely desertified land first increased then decreased (Fig. 6 [Figure 6: see original paper]). From 1994 to 2019, China conducted six national desertification monitoring sessions (every five years), showing continuous desertified land area decrease during four post-1999 monitoring periods (Fig. 9 [Figure 9: see original paper]). Desertification reversed, with lightly desertified land expanding, moderately desertified land remaining stable, and severely desertified land shrinking—consistent with this study' s findings.

The Kumtagh Desert is an uninhabited area almost unaffected by human activities. Scientific exploration and physical geographical research began in 2005. With extremely arid climate (<50 mm annual precipitation) and almost no vegetation, it consists mostly of shifting sand dunes (Dong et al., 2008). Only two articles address Kumtagh Desert landscape dynamics (Wang et al., 2003, 2004), which could not be included in meta-analysis. Research shows little overall landscape change from 1975 to 2007 (Zhao and Fu, 2003; Wu et al., 2013). Artificial oasis area increased significantly while natural vegetation (e.g., salt marshes) decreased significantly, and desert area increased slightly under climate influence (Wu et al., 2013). This desert' s desertification change trend was consistent with this study' s western region findings.

This study used a random effects model in meta-analysis to minimize impacts of variability across study region characteristics, remote sensing data sources, and desertification classification criteria. Nevertheless, these factors still affected findings to some extent, highlighting the need for methodological refinements in future studies.

4.2 Impact of Climate Factors on Desertification

Many studies demonstrate that climate is a crucial desertification process factor (Zhang et al., 2018; Xiu et al., 2024). Temperature, precipitation, and wind speed are primary climatic factors affecting desertification (Zhang et al., 2020). Using meteorological station data around the eight deserts and four sandy lands (Fig. 1 [Figure 1: see original paper]), we analyzed annual average temperature, annual precipitation, and annual average wind speed from 1985 to 2019. Since 1985, all deserts and sandy lands except Hulunbuir Sandy Land showed significant temperature increases ($P<0.010$; Fig. 10 [Figure 10: see original paper]). Annual precipitation increased significantly in the eastern region' s Mu Us Sandy Land ($P<0.050$), while other deserts and sandy lands showed slight decreases, though western region desert precipitation increased. Eastern region deserts and sandy lands except Hulunbuir showed decreased annual average wind speed, while western region deserts except Ulan Buh and Qaidam Basin showed increased wind speed. Studies show warming and wetting benefit vegetation restoration (Shi et al., 2007; Xiu et al., 2024). Wind activity significantly influences desertification, with declining wind speeds reducing aeolian erosion and facilitating vegetation recovery. Eastern region' s slightly decreased wind speeds and slightly decreased precipitation in most sandy lands were conducive to desertification reversal. Western region' s increased wind speeds and slightly increased precipitation created conditions conducive to desertification expansion.

4.3 Impact of Human Activities on Desertification

Human activities play a crucial role in desertification processes. During the 1960s and 1970s, rapid population growth increased natural resource demand, placing greater pressure on land and disrupting fragile ecological balance (Duan et al., 2019). Irrational economic activities accelerated desertification expansion, including excessive sandy land cultivation (Li et al., 2018), overgrazing (Bo et al., 2013), and water resource overuse (Wang et al., 2008). However, the 1980s land contracting system greatly alleviated overcultivation and overgrazing, curbing desertification expansion (Fei et al., 2025). Since the 1990s, socioeconomic development led the Chinese government to recognize sustainable development' s importance, adjusting policies to increase fragile environment protection and desertification prevention efforts.

Since 2000, in addition to the Three-North Shelterbelt Development Program (implemented in 1978), ecological construction projects including the Natural Forest Conservation Program, Grain for Green Program, and Beijing-Tianjin Sandstorm Source Control Project were implemented successively, accelerating desertification control and reversing expansion trends. In recent years, desertification control has received widespread societal attention, accompanied by growing ecological conservation awareness and increased government investment, accelerating reversal speed.

From 1970 to 2019, the western region experienced less desertified land area change compared to the eastern region. This is attributable to the western region' s arid conditions, low population density, and extensive native deserts dating to geological history. Desertification here primarily resulted from water resource overuse and excessive groundwater extraction, affecting limited spatial scales around oases. In contrast, the eastern region' s semi-arid and dry sub-humid climate, higher population density, and intensive human activities (particularly cultivation and overgrazing) induced widespread desertification across extensive areas. During ecological construction project implementation, eastern region desertified land was easier to control than western region land.

Desertification is land degradation caused by climate change and human activities' combined effects. Arid climate provides background conditions for desertification occurrence. Normally, climate change affects desertification through long-term processes, whereas human activities induce more immediate impacts. The interaction between climate change and human activities cannot be ignored (Li et al., 2021). Revegetation reduces surface albedo and affects wind conditions by altering surface roughness. Vegetation restoration makes local climate more humid by slowing surface runoff and reducing evaporation (Feng et al., 2021). This analysis indicates that in the current global change context, human intervention measures such as ecological engineering construction are essential to curb desertification expansion and mitigate impacts, while climate change' s long-term impacts remain critical considerations.

5 Conclusions

This study collected published research cases on eight major deserts, four major sandy lands, and surrounding areas in China, using meta-analysis to examine desertification dynamics from 1970 to 2019. At the spatial scale, China' s overall desertification development first expanded then reversed from 1970 to 2019, with distinct dynamics between the semi-arid/dry sub-humid eastern region and the arid western region. In the eastern region, lightly desertified land area percentage increased while moderately and severely desertified land decreased. In the western region, lightly desertified land area percentage increased slightly while moderately and severely desertified land decreased slightly. Overall, desertification reversed during the study period. At the temporal scale, desertification expanded from 1980 to 1999 and reversed after 2000, with accelerated reversal since 2010. Since 1990, under global climate change, the eastern region experienced increased annual precipitation and decreased annual average wind speed—climate factors conducive to desertification reversal, with ecological construction projects playing key roles. The western region showed increased annual precipitation and annual average wind speed (with localized decreases). Although ecological construction projects helped control and restore certain desertified areas, desertified land area percentage changed relatively little.

This study provides adequate insights for governmental decision-makers and ecologists. Future research should implement long-term desertification dynamics monitoring schemes incorporating longer historical perspectives to better understand expansion and reversal trends.

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Appendix

Fig. S1 Area percentage change of desertified land with different desertification degrees in major deserts and sandy lands from 1970 to 2019. (a) Hulunbuir Sandy Land; (b) Horqin Sandy Land; (c) Otindag Sandy Land; (d) Mu Us

Sandy Land; (e) Hobq Desert; (f) Ulan Buh Desert; (g) Tengger Desert; (h) Badain Jaran Desert; (i) Qaidam Basin Desert; (j) Gurbantunggut Desert; (k) Taklimakan Desert. Kumtagh Desert data were excluded due to lack of valid data.

Table S1 P value in the Egger regression during four periods

Region	Period	ES of lightly desertified land	ES of moderately desertified land	ES of severely desertified land
Whole region				
Western region				
Eastern region				

Note: ES, effect size.

Note: Figure translations are in progress. See original paper for figures.

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