Monitoring rock desert formation caused by two different origins (ice-snow melting and drying) in the Qinghai-Tibet Plateau of China by considering topographic and meteorological elements postprint

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Abstract

Monitoring rock desert formation caused by two different origins (ice-snow melting and drying) through remote sensing is crucial for understanding the interaction between the underlying surfaces of different rock desert types and land-atmosphere systems, as well as the relationship between bare land and soil erosion. Although significant progress has been made in remote sensing monitoring of desert areas, accurate classification and remote sensing identification of rock desert types based on formation mechanisms remain lacking. In this study, the northern and southern slopes of the eastern Kunlun Mountains in the northern Qinghai-Tibet Plateau were selected as the study area. Landsat Operational Land Imager (OLI) data, digital elevation models, and gridded precipitation and temperature data were used as data sources. By identifying bare areas based on the Normalized Difference Vegetation Index (NDVI), we employed a multi-element fusion method using contours, isotherms, and isohyets to identify rock desert types in ice-snow melting and dry areas. The results showed that: (1) The rock desert areas identified by remote sensing based on topographic and meteorological elements achieved high accuracy, with an overall accuracy of 88.45% and a Kappa coefficient of 0.77. The multi-element fusion method of contours, isotherms, and isohyets could effectively identify rock desert types in ice-snow melting and dry areas. (2) The optimal segmentation ranges for ice-snow melting and dry areas were the 3600 m contour, −2°C to 2°C isotherms, and 100–130 mm isohyets. Areas with elevation below 3600 m, annual average temperature above 2°C, and average annual precipitation below 100 mm were classified as rock desert in dry areas. The range of −2°C to 2°C isotherms and 100–130 mm isohyets served as the transition zone between ice-snow melting

and dry areas. Areas with elevation above 3600 m, annual average temperature below −2°C, and average annual precipitation above 130 mm were classi

Full Text

Monitoring Rock Desert Formation Caused by Two Different Origins (Ice-Snow Melting and Drying) in the Qinghai-Tibet Plateau of China by Considering Topographic and Meteorological Elements

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Abstract: Monitoring rock desert formation caused by two different origins (ice-snow melting and drying) through remote sensing is crucial for understanding the interaction between the underlying surfaces of different rock desert types and land-atmosphere systems, as well as the relationship between bare land and soil erosion. Although significant progress has been made in remote sensing monitoring of desert areas, accurate classification and remote sensing identification of rock desert types based on formation mechanisms remain lacking. In this study, the northern and southern slopes of the eastern Kunlun Mountains in the northern Qinghai-Tibet Plateau were selected as the study area. Landsat Operational Land Imager (OLI) data, digital elevation models, and gridded precipitation and temperature data were used as data sources. By identifying bare areas based on the Normalized Difference Vegetation Index (NDVI), we employed a multi-element fusion method using contours, isotherms, and isohyets to identify rock desert types in ice-snow melting and dry areas. The results showed that: (1) The rock desert areas identified by remote sensing based on topographic and meteorological elements achieved high accuracy, with an overall accuracy of 88.45% and a Kappa coefficient of 0.77. The multi-element fusion method of contours, isotherms, and isohyets could effectively identify rock desert types in ice-snow melting and dry areas. (2) The optimal segmentation ranges for ice-snow melting and dry areas were the 3600 m contour, −2°C to 2°C isotherms, and 100–130 mm isohyets. Areas with elevation below 3600 m, annual average temperature above 2°C, and average annual precipitation below 100 mm were classified as rock desert in dry areas. The range of −2°C to 2°C isotherms and

100–130 mm isohyets served as the transition zone between ice-snow melting and dry areas. Areas with elevation above 3600 m, annual average temperature below −2°C, and average annual precipitation above 130 mm were classified as rock desert in ice-snow melting areas. (3) The identification accuracy of bare areas based on the NDVI method was satisfactory, with plain bare areas showing generally better accuracy than mountain bare areas. This remote sensing identification method considers not only topographic factors that significantly influence the spatial distribution of the two rock desert types but also meteorological factors, providing a scientific reference for effective identification of these two rock desert types.

Keywords: rock desert in ice-snow melting areas; rock desert in dry areas; contours; isotherms; isohyets; Qinghai-Tibet Plateau

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1 Introduction

A rock desert is a geographical landscape with sparse or bare surface vegetation formed under drought or alpine climate conditions [?, ?, ?, ?], affecting the production and livelihood of over 110 countries and regions worldwide, particularly in arid areas [?, ?]. Since the 1990s, environmental and social problems caused by rock desertification have become key factors hindering sustainable development in arid, semi-arid, and sub-humid regions, which account for 41% of the global land area [?, ?, ?]. Land surface properties control the distribution of water and energy fluxes, while rock desert expansion alters underlying surface characteristics. These changes in surface properties modify land surface parameters, which feed back to the atmosphere through energy redistribution and subsequently affect near-surface climate. Near-surface temperature is particularly sensitive to these changes, influencing not only atmospheric circulation but also regional and global climate [?, ?, ?].

The Qinghai-Tibet Plateau, located at elevations exceeding 4000 m above sea level, is the world's largest and highest plateau, known as the "Third Pole" and the "Roof of the World" [?, ?, ?, ?]. The plateau is considered one of the most sensitive regions to global climate change [?, ?, ?]. Through the combined influence of summer monsoon, winter monsoon, and mid-latitude westerly winds, a cold and dry continental climate prevails across the plateau [?, ?, ?]. Strong winter winds cause frequent frost weathering and intense wind erosion, promoting the formation of sandy materials [?, ?]. Consequently, the unique geographical location, strong winds, abundant sand sources, and cold-dry climate create favorable conditions for plateau rock desert development [?, ?, ?]. Currently, existing and potential desertification land on the Qinghai-Tibet Plateau covers approximately 3.93$×10^{5}$ km^2 (15.10% of the plateau's total area) and 2.99$×10^{4}$ km^2, respectively [?, ?]. The northern plateau represents a national key desertification area, primarily distributed in the Qaidam, Gonghe, and Qinghai Lake basins and the Three-River Headwaters Region [?, ?]. Furthermore, rock desertification processes on the plateau are gradually intensifying [?, ?, ?].

Remote sensing is an important tool for monitoring and evaluating rock desert [?, ?, ?], providing high-precision data across extensive areas [?, ?]. In recent decades, numerous scholars have monitored desertification on the Qinghai-Tibet Plateau using remote sensing [?, ?, ?, ?, ?]. Existing remote sensing monitoring primarily includes index extraction methods based on NDVI and image classification methods (visual interpretation and computer-automated classification) [?, ?, ?, ?, ?, ?], providing scientific support for monitoring desertification dynamics. However, most studies focus on monitoring desertification degree, lacking accurate classification and remote sensing identification of rock desert types based on formation mechanisms.

The surface material of different rock desert types controls energy flux and water distribution, playing a vital role in the climate system. Land-atmosphere interactions are important drivers of climate [?, ?], with energy, momentum, and matter exchange between atmosphere and surface being key to these interactions, affecting local and regional atmospheric circulation and climate change [?, ?]. Various soil erosion types exist on the Qinghai-Tibet Plateau. In ice-snow melting areas, rock desert formed through combined freeze-thaw, gravity, wind, and fluvial erosion can be termed "rock desert in ice-snow melting areas." In dry areas, rock desert formed by wind erosion of drying denudation can be termed "rock desert in dry areas." Both rock desert types are products of climate change, but their soil erosion dynamics and underlying surface types differ completely. For rock desert in ice-snow melting areas, climate warming and snowline retreat continuously expose more bedrock, with surface weathering particles becoming smaller due to multiple erosion processes. In contrast, rock desert in dry areas is bare land dominated by precipitation stress, with large landscape gradients, poor soil and water conservation capacity, and low soil fertility. Wind erosion changes the particle size and spatial distribution of rock desert. The spatial distribution of both rock desert types is directly related to elevation, temperature, and precipitation. Therefore, recognizing the interaction between bare land and soil erosion, as well as the relationship between different rock desert underlying surfaces and land-atmosphere types, is important for identifying rock desert in ice-snow melting and dry areas through remote sensing based on comprehensive topographic and meteorological factors.

This study selected the Yuzhu Peak region in the eastern Kunlun Mountains of the northern Qinghai-Tibet Plateau as the sampling area. Using 2020 Landsat 8 OLI remote sensing data as the primary source, with digital elevation models (DEM) and meteorological raster data as auxiliary data, we constructed an optimal remote sensing identification method for different rock desert types based on contours, isotherms, and isohyets, according to descriptions of formation mechanisms, material composition, and spatial distribution of rock desert in ice-snow melting and dry areas of the Qinghai-Tibet Plateau. This method provides information support for deepening our understanding of the interaction between bare land and soil erosion and the relationship between different rock desert underlying surfaces and land-atmosphere types, and is valuable for ecological environment maintenance and Qinghai-Tibet Plateau national park construction.

2 Comparison of Rock Desert Types in Ice-Snow Melting and Dry Areas

Rock desert is a desert type formed by freeze-thaw erosion, wind erosion, gravity erosion, fluvial erosion, and other natural factors, as well as human activities, in arid, semi-arid, and dry sub-humid regions. Its manifestations include soil coarsening, decreasing nutrient and water content, and significantly reduced vegetation coverage and productivity. Based on surface weathered material particle size, rock desert can be divided into bare rock, bare stone, bare gravel, bare sand, and bare soil [**?**, **?**, **?**]. According to different driving forces, we classified rock desert into ice-snow melting and dry areas.

2.1 Formation Mechanism of the Two Rock Desert Types

Both rock desert types are products of climate, but their mechanisms differ. Rock desert in ice-snow melting areas forms as climate warming melts permanent snow and glaciers, causing snowline retreat and exposing bare land. Rock desert in dry areas forms due to insufficient precipitation that cannot meet minimum vegetation growth requirements. The former changes land cover from ice and snow to bare land, while the latter is bare land formed by precipitation stress. Furthermore, their soil erosion dynamics differ: rock desert in ice-snow melting areas results from combined freeze-thaw, gravity, wind, and fluvial erosion, whereas that in dry areas is primarily caused by wind erosion of drying denudation.

2.2 Differences in Material Composition and Spatial Distribution Characteristics

2.2.1 Rock Desert in Ice-Snow Melting Areas The material composition of rock desert in ice-snow melting areas includes bare rock, bare stone, bare gravel, bare sand, and bare soil, with various types distributed in a staggered pattern, predominantly bare rock and bare stone [Figure 1: see original paper]. Figure 1 illustrates the material composition and spatial distribution characteristics based on a typical ice-snow melting area, hand-painted by Prof. Shi Peijun during the Second Qinghai-Tibet Plateau Scientific Expedition on July 28, 2021. The area is located at the junction of Maqên County and Jigzhi County in Golog Tibetan Autonomous Prefecture, Qinghai Province, in the plateau's hinterland. Along vertical gradient transitions, geomorphic types change from foothills to mountain top: from 4000–4500 m planation surfaces (T4) and 5000–5500 m planation surfaces (T5) to plateau mountain regions mostly between 5000–6000 m (M) with increasing elevation. Rock desert types occur in the 4000–6000 m elevation range, with bare soil, bare sand, bare gravel, bare stone, and bare rock distributed from bottom to top, covered by ice and snow above 6000 m. Due to the wide distribution of ice-snow melting areas across the Qinghai-Tibet Plateau and varying geographical environments, vertical gradient distribution types are not always as complete as the five types shown in Figure 1, and elevation ranges fluctuate between 4000–6000 m.

2.2.2 Rock Desert in Dry Areas Compared with ice-snow melting areas, dry area rock desert shows obvious differences in material composition and spatial distribution. While material composition also includes bare rock, bare stone, bare gravel, bare sand, and bare soil, dry area rock desert is distributed horizontally and in patches, primarily in inland basins and along both sides of river valleys in dry areas [Figure 2: see original paper]. Figure 2, hand-painted by Prof. Shi Peijun in the Qaidam Basin on July 31, 2021, shows mountains located on the southern side of the valley plain with east-west orientation. Within Figure 2's scope, geomorphic types transition from mountain foot to top, as well as from piedmont plain and alluvial fan to dry mountain. Bare rock only occurs in dry mountain areas with large slopes, bare stone is primarily distributed in proluvial fan areas below dry mountains, while bare sand, bare gravel, and bare soil are distributed in alluvial-proluvial plains and lacustrine alluvial plains. The Qaidam Basin primarily contains vast gobi, with small distributions of dry mountain areas and piedmont alluvial fans, resulting in limited bare rock and bare stone areas. Bare gravel is distributed along both sides of river valleys in dry areas, while bare sand and bare soil are distributed across wide basins.

3 Methodology

3.1 Study Area and Data

3.1.1 Study Area The study area (35°21′–37°39′N, 93°25′–96°15′E) is located in the northern Qinghai-Tibet Plateau, centered on Yuzhu Peak, the highest peak in the eastern Kunlun Mountains, covering a total area of 6.2$\times10^{4}$ km^2. The region includes the western Nomhon River, southeastern Dong Taijnar Lake, and northwestern Sonam Darjee Conservation Station [Figure 3: see original paper]. The Kunlun Mountains traverse this area, with the Qaidam Basin to the north and the Yushu Plateau to the south. The Qaidam Basin is an arid area with scarce precipitation (average annual precipitation <100 mm) and flat terrain, while the Yushu Plateau features permafrost and typical periglacial geomorphic characteristics. The climate is a typical plateau alpine climate with large topographic fluctuations. Due to obvious climate and geomorphology differences between north and south, combined with unique geographical location, strong winds, abundant sand sources, and cold-dry climate, the region provides favorable conditions for rock desert occurrence and serves as an ideal area for studying both rock desert types.

3.1.2 Data Collection and Image Preprocessing Data used in this study include: (1) Landsat 8 OLI imagery with Path/Row numbers P136R034, P136R035, P137R034, and P137R035, acquired on August 30, 2020, September 15, 2020, September 22, 2020, and September 22, 2020, respectively. The spatial resolution is 30 m$×30mwithcloudcover < 10×30m, obtainedfromtheChinaGeospatialDataCloudwebsite(https : //www.gscloud.cn/).(3)TemperatureandprecipitationrasterdatafromtheNationalQinghai− TibetPlateauScientificDataCenter(http : //data.tpdc.ac.cn/)forJanuary1991−December2018with1km×$1 km spatial resolution [?, ?].

Image preprocessing includes geometric correction, radiometric calibration, atmospheric correction, terrain correction, and projection transformation. Geometric correction eliminates geometric errors, ensuring ground objects appear in the same position in corrected images. Radiometric calibration converts pixel digital numbers to radiance, obtaining top-of-atmosphere reflectance. Atmospheric correction eliminates atmospheric absorption and scattering effects on ground object reflectance. Terrain correction eliminates complex terrain effects on radiance to obtain true ground reflectance. Finally, OLI images, DEM data, and temperature/precipitation raster data are projected to the Albers equal-area conic projection.

3.2 Contour Extraction

DEM is a dataset that digitally simulates ground terrain through limited surface elevation information, describing ground elevation through regular grid points within a certain range. DEM reflects regional geomorphology spatial distribution and provides approximate terrain description for determining comprehensive scale [?, ?]. Contours are the most effective expression of three-dimensional topography on a two-dimensional plane, reflecting surface fluctuation and morphology characteristics [?, ?]. Contours refer to closed curves connecting adjacent points with equal elevation on topographic maps [?, ?]. Although theoretically closed, contours may appear as open curves with endpoints on map frame boundaries due to map extent limitations.

In the study area, elevation ranges from 2442 m to 6212 m, with relative relief of 3770 m. Mountain areas feature large slopes and complex surface fragmentation. Generally, temperature decreases by 0.6°C per 100 m. To effectively connect topographic and meteorological elements, we selected a 100 m vertical interval for contour extraction using ArcGIS 10.5. The contour tool generates contours from regular grid DEM data sources.

3.3 Extraction of Isotherms and Isohyets

Temperature and precipitation are fundamental climate change elements that reflect regional dry-wet conditions and serve as important indicators for natural division between dry and wet areas. Both are crucial climatic factors affecting rock desert type spatial distribution [?, ?]. Climatic characteristic lines (isotherms and isohyets) are important reference indices for natural zoning and can serve as effective dividing lines for rock desert distribution ranges formed by climate in ice-snow melting and dry areas.

The implementation process involves: First, calculating annual average temperature and average annual precipitation from multi-year meteorological data. Since meteorological data are formatted monthly with large data volumes, MATLAB code (Version R2019a) was developed to: (1) average monthly temperature data from 1991–2018 to obtain annual average temperature and calculate multi-year mean temperature; and (2) accumulate monthly precipitation data from 1991–2018 into annual precipitation and calculate average annual precipitation. This yields mean temperature and precipitation raster TIFF data with required temporal resolution. Second, using ArcGIS 10.5 tools such as reclassification and raster-to-vector conversion, we extracted isohyets at 10 mm intervals and isotherms at 1°C intervals in the study area.

3.4 Remote Sensing Identification of Two Rock Desert Types Based on Multi-Element Overlay Analysis

Through multi-source data integration, we identified bare areas using the NDVI method and adopted multi-element fusion of contours, isotherms, and isohyets to efficiently extract the two rock desert types with high precision [Figure 4: see original paper].

3.4.1 Identification of Bare Areas Based on NDVI The study area includes mountain and plain geomorphic types, with P136R035 and P137R035 primarily mountainous and P136R034 and P137R034 primarily plain areas [Figure 5: see original paper]. Mountain areas contain various land use types including vegetation, bare land, water, residential land, and ice-snow covered land, with relatively fragmented spatial distribution and no obvious characteristics. Bare land in mountain areas is primarily caused by ice-snow melting, distributed in small, patchy patterns within ice-snow melting zones. Plain areas include vegetation, bare land, water, residential, and industrial land, with bare land primarily caused by drought, distributed in large patches.

Bare and non-bare areas have different material compositions and geomorphology types, with vegetation coverage in bare areas lower than in non-bare areas. NDVI is the most widely used index for reflecting vegetation coverage and an important distinguishing factor between bare and non-bare areas [**?**, **?**]. NDVI is the most efficient method among all vegetation and drought indices for bare areas [**?**, **?**]. The NDVI calculation formula is:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where RED and NIR are reflectance values of red and near-infrared bands, respectively, ranging from –1 to 1. Generally, NDVI < 0 indicates non-vegetation areas, while NDVI > 0 represents vegetation areas. To effectively determine NDVI thresholds for bare and non-bare areas, we divided images into 1 km$×$1 km grids using the fishnet tool, extracted NDVI values at each grid center point, and statistically analyzed NDVI threshold ranges for land use types in mountain and plain areas .

The final NDVI thresholds for bare areas were determined as –0.10 to 0.12 in plain areas and 0.00 to 0.08 in mountain areas.

3.4.2 Identification of Two Rock Desert Types Considering Topographic and Meteorological Elements Based on formation mechanisms, spatial distribution of the two rock desert types is determined by elevation, temperature, and precipitation. For bare area identification results, contour results from topographic elements were overlain with OLI images to determine the optimal segmentation contour between ice-snow melting and dry area rock desert. Using isoline element overlay analysis, we superposed the optimally divided contours with isotherms and isohyets to determine the isotherm and isohyet ranges closest to the optimal contour distribution. The combination of three isoline ranges represents the optimal dividing line combination for identifying rock desert in ice-snow melting and dry areas.

3.5 Accuracy Verification Method

Evaluation of identification results is crucial in remote sensing monitoring and measures identification reliability. Accuracy verification determines processing accuracy by comparing actual data with processed data. The most commonly used method is the confusion matrix, calculated by comparing each measured pixel's position and category with corresponding identification results [**?**, **?**]. Each matrix column represents actual measured information, with column values equal to the number of measured pixels corresponding to each identification category; each row represents identification result information, with row values equal to the number of identification result pixels in each measured category. The confusion matrix comprehensively reflects identification accuracy [**?**, **?**].

To verify remote sensing identification accuracy, we conducted GPS field sampling in the study area from September 24–29, 2021. Based on traffic accessibility, we collected sampling points from bare areas, non-bare areas, dry area rock desert, ice-snow melting area rock desert, and transition zones. Each sampling point was located by GPS, recording geographic coordinates, elevation, land use type, and vegetation coverage, yielding 248 sampling points total.

4 Results

4.1 Accuracy Verification

4.1.1 Accuracy Verification of Bare Area Identification GPS sampling collected 139 points in bare areas and 109 in non-bare areas. In plain areas, 92 sampling points were in bare areas and 40 in non-bare areas (primarily vegetation). In mountain areas, bare areas are primarily distributed in ice-snow melting zones that are difficult to access, yielding 47 samples, while 69 samples were collected in non-bare areas (primarily vegetation with small ice-snow covered areas). Accuracy verification results for plain, mountain, and entire study areas based on confusion matrices are shown in .

Table 2 shows that bare area identification based on NDVI achieved good accuracy, with overall accuracy of 93.95% and Kappa coefficient of 0.88. Plain area identification accuracy was better than mountain areas. With fewer land types and patchy bare area distribution in plains, identification accuracy was high, reaching a Kappa coefficient of 0.91. Mountain bare areas, primarily caused by ice-snow melting with small, fragmented patches, showed slightly lower accuracy but still achieved a Kappa coefficient of 0.82, meeting study requirements.

4.1.2 Accuracy Verification of Ice-Snow Melting Area, Dry Area, and Transition Zone Identification Remote sensing identification results for ice-snow melting and dry area rock desert were obtained using integrated contours, isotherms, and isohyets. GPS sampling collected 139 points in bare areas, including 42 in ice-snow melting areas, 88 in dry areas, and 9 in transition zones. Accuracy verification results based on confusion matrices are shown in .

Table 3 shows that the combined dividing line ranges from integrated contours, isotherms, and isohyets achieved good identification accuracy for both rock desert types, with overall accuracy of 88.45% and Kappa coefficient of 0.77. Dry area rock desert identification accuracy was better than ice-snow melting areas. Transition zone accuracy was relatively low, as it is located between the two rock desert types, resulting in high probability of misclassification. This may also relate to the small number of transition zone sampling points. The dividing line considers both topographic factors significantly influencing spatial distribution and meteorological factors, providing scientific reference for effective identification of the two rock desert types.

4.2 Remote Sensing Identification Results of Bare Areas

NDVI results were calculated using 2020 Landsat 8 OLI images with similar sampling times [Figure 6: see original paper]. In plain areas [FIGURE:6a and b], NDVI results show three colors: white for vegetation, black for water, residential, and industrial land, and gray for bare areas. Mountain area results [FIGURE:6c and d] show more colors: white and light gray for vegetation, black for water, residential, and industrial land, dark gray for ice-snow covered areas, and medium gray for bare areas.

Based on statistical results of NDVI thresholds from typical sampling points, plain bare area NDVI threshold ranges are slightly wider than mountain bare areas. Wider spatial distribution of bare areas corresponds to larger NDVI threshold ranges; conversely, more land types result in smaller spatial distribution ranges and more concentrated NDVI thresholds. Bare area extent determined by the NDVI method is shown in [Figure 7: see original paper], covering 3.72$×10^{4}$ km^2, or 60.00% of the study area.

4.3 Remote Sensing Identification Results of Two Rock Desert Types

Extraction results for 100 m interval DEM contours, 1°C interval isotherms, and 10 mm interval isohyets are shown in [Figure 8: see original paper]. The study area has large topographic fluctuations with 3770 m relative height difference, and 100 m interval contours remain dense, trending low in the north and high in the south. Taking the northern Kunlun Mountains as the boundary, Qaidam Basin contours range from 2500–3600 m, concentrated in 2700–3300 m. The Yushu Plateau ranges from 3600–6200 m. From 1991–2018, annual average temperature was higher in the north and lower in the south, with Qaidam Basin isotherms between 2°C–7°C and Yushu Plateau isotherms between –9°C–5°C. Average annual precipitation was lower in the north and higher in the south, with Qaidam Basin isohyets between 50–100 mm and Yushu Plateau isohyets between 100–240 mm.

Based on overlay analysis of topographic contour results and OLI images, we determined the optimal dividing contour between ice-snow melting and dry area rock desert to be 3600 m. Through contour element overlay, we superposed optimal contours with isotherms and isohyets to determine ranges closest to optimal contour distribution. There is an obvious negative correlation between temperature and elevation, with the –2°C to 2°C isotherm range consistent with the 3600 m contour. Therefore, the –2°C to 2°C isotherm range was set as the dividing line between rock desert types. Due to southwest monsoon influence, as water vapor from the Indian Ocean moves from the southern to northern slopes of the Kunlun Mountains, isohyets change from dense to sparse at 100–130 mm. Thus, the 100–130 mm isohyet range was set as the dividing line [Figure 9: see original paper].

Figures 8 and 9 show that the 3600 m contour, –2°C to 2°C isotherms, and 100–130 mm isohyets are spatially close. The 3600 m contour and –2°C to 2°C isotherms are influenced by Kunlun Mountains trends, with similar patterns. Isohyets practically coincide with isotherms on the east side but are slightly north on the west side, primarily due to the negative temperature-elevation correlation and precipitation decrease influenced by windward slope gradient and aspect. Therefore, areas with elevation <3600 m, annual average temperature >2°C, and precipitation <100 mm are classified as dry area rock desert. The –2°C to 2°C isotherm and 100–130 mm isohyet range represents the transition zone. Areas with elevation >3600 m, annual average temperature <–2°C, and average annual precipitation >130 mm are classified as ice-snow melting area rock desert. Dry area rock desert covers 3.14$×10^{4}$ km^2 (84.40% of bare areas), ice-snow melting area rock desert covers 0.34$×10^{4}$ km^2 (9.14% of bare areas), and the transition zone covers 0.24$×10^{4}$ km^2 (6.46% of bare areas).

5 Discussion

5.1 Applicability Evaluation of NDVI-Based Bare Area Identification

The study region's bare areas include plain and mountain types, with different spatial distribution ranges, land type numbers, and identification accuracies. NDVI segmentation results for different land class densities in plain and mountain areas are shown in [Figure 10: see original paper] and [Figure 11: see original paper].

Plain areas are primarily located in the dry Qaidam Basin, dominated by bare land with small proportions of water, residential, industrial land, and vegetation. Each type shows high spatial heterogeneity, with obvious contiguous bare land distribution. Figure 10 shows good segmentation between bare areas and other land types (water, residential, industrial, vegetation). Boundaries for residential/industrial land and water are clear, and vegetation-bare area boundaries are distinctly demarcated. Roads and water in residential/industrial land are well identified. Therefore, NDVI shows high applicability for dry bare land in plain areas.

Most mountain areas are located on the Yushu Plateau, dominated by vegetation, with bare land typically distributed in fragmented patterns within ice-snow melting zones at high elevations. Figure 11 shows that bare areas can be distinguished from ice-snow covered areas and vegetation, though some rivers are misclassified as vegetation. In extremely high mountain areas (i.e., Yuzhu Peak), type discrimination is poor, with ice-snow covered areas misclassified as water and partial misclassification of bare land and water. For bare land around large water areas, discrimination is high. NDVI identification of mountain bare land is slightly lower than for plain dry bare land, which accuracy evaluation confirms, but still supports rapid, efficient monitoring of mountain bare areas. In conclusion, NDVI-based bare area identification shows good applicability. To further improve mountain bare land identification accuracy, multi-index or multi-indicator combinations could be considered in future work.

5.2 Uncertainty Evaluation of Isoline Combination Results

Rock desert identification results in ice-snow melting and dry areas are based on meteorological grid data from 1991–2018. To explore isoline combination uncertainty, we plotted annual average temperature and average annual precipitation trend charts [Figure 12: see original paper].

Figure 12 shows temperature rising at 0.8°C/10 a and precipitation increasing at 32.8 mm/10 a in the study area from 1991–2018. With future temperature and precipitation changes, isotherms and isohyets are expected to migrate, altering the optimal dividing line combination between ice-snow melting and dry areas. Recent years have shown warming and humidification trends in the eastern Kunlun Mountains consistent with the Qinghai-Tibet Plateau. As temperature and precipitation change, isotherm and isohyet ranges will fluctuate. Temperature increase raises isotherm values, while precipitation increase raises isohyet values. Isotherms and isohyets within the combination are expected to increase, slightly changing the ranges of the two rock desert types.

5.3 Uncertainty of Rock Desert Classification System

Desert type classification merges groups according to desert land similarities and differences. Based on external forces and causes, desert can be divided into wind-eroded desert, water-eroded desert, freeze-thaw desert, and land salinization. By climate type: arid desert, semi-arid desert, and sub-humid desert. By desertification degree: mild, moderate, and severe desertification. By surface composition particle size: stony desert, gravel desert, sandy desert, and salt desert [?, ?, ?, ?]. Using climate zoning as the main indicator combined with external forces and degraded land characteristics, Qinghai-Tibet Plateau desert can be divided into arid desert and freeze-thaw desert [?, ?, ?], with freeze-thaw desert including ice-snow melting area rock desert [?, ?].

This paper classifies Qinghai-Tibet Plateau rock desert into ice-snow melting area and dry area types, which helps distinguish rock desert by formation mechanism. Based on field investigation results, we divided rock desert into bare rock, bare stone, bare gravel, bare sand, and bare soil according to surface weathered material particle size, limited to the study area scope. Ice-snow melting area rock desert is primarily bare rock and bare stone, while dry area rock desert is mainly bare gravel, bare sand, and bare soil. Weathered rock desert particle size in ice-snow melting areas is larger than in dry areas because ice-snow melting area rock desert has only been exposed in recent decades with lower weathering degree. Dry area rock desert, affected by long-term combined wind, water, gravity, and freeze-thaw erosion, has relatively smaller weathered material particle size. Significant differences in physical and geographical characteristics exist among Qinghai-Tibet Plateau regions, and specific classification types should be further rationally divided according to regional rock desert material composition structure.

6 Conclusions

(1) The multi-element fusion method using contours, isotherms, and isohyets can effectively identify rock desert in ice-snow melting and dry areas. Accuracy verification shows high multi-factor identification accuracy, with overall accuracy of 88.45% and Kappa coefficient of 0.77. This method considers both topographic factors significantly influencing spatial distribution of the two rock desert types and meteorological factors, providing scientific reference for effective identification.

(2) The optimal dividing ranges for ice-snow melting and dry area rock desert are the 3600 m contour, −2°C to 2°C isotherms, and 100–130 mm isohyets. Based on multi-factor fusion identification, areas with elevation <3600 m, annual average temperature >2°C, and average annual precipitation <100

mm are dry area rock desert. The –2°C to 2°C isotherm and 100–130 mm isohyet range is the transition zone. Areas with elevation >3600 m, annual average temperature <–2°C, and average annual precipitation >130 mm are ice-snow melting area rock desert.

(3) NDVI-based plain bare area identification accuracy is better than mountain bare areas. Plain areas have fewer land types with widely distributed patchy bare land. Mountain bare areas are primarily caused by ice-snow melting, distributed in small, fragmented patches within ice-snow melting zones. Plain bare area NDVI threshold range is –0.10 to 0.12, slightly wider than mountain bare areas (0.00 to 0.08). Bare areas cover 3.72$×10^{4}$ km^2, accounting for 60.00% of the study area.

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