

Application of Remote Sensing in Desertification Monitoring

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Abstract. Desertification has become one of the greatest international concerns in recent decades. This study mainly focuses on the significance and necessity of applying remote sensing to improve efficiency in desertification monitoring. Results show that applications of remote sensing in desertification monitoring have shown advantages and promises of development in the future. Satellite images and unmanned aerial vehicle technology are two major sources of remote sensing data. This study also contains specific applications of remote sensing techniques, including normalized difference vegetation index (NDVI), land cover classification, and spectral mixture analysis (SMA). NDVI measures the vegetation cover to reflect potential desertification but fails to offer a comprehensive picture of the desertification status of an area. While land cover classification identifies different types of land use to monitor desertification, track changes over time, and find potential environmental stressors, the technique requires huge investments in technology and labor. SMA, the sub-pixel classification technique, provides a detailed analysis while consuming significant computing resources and time. This study also provides prospects for future developments of data acquisition and analysis approaches in desertification monitoring using remote sensing. Making suggestions on future research topics and possible methodologies, this study hopes to inspire further research in this area to better deal with the global issue of desertification.

Keywords: Desertification, remote sensing, NDVI, classification, vegetation.

1. Introduction

Desertification, the process when lands lose vegetation and form desert-like conditions, has significant international impacts [1, 2]. Estimation shows that land degradation and desertification affected over 1.4 billion people, among which 74% are in poverty. Drought and desertification are also destroying ecosystems and causing the loss of millions of hectares of arable land annually [3]. While desertification has been recognized by the United Nations as one of the greatest international concerns, combating desertification to reduce biodiversity loss, global poverty, and human-induced global climate change is urgent and crucial [1, 3]. Traditional means to understand the desertification process rely on analyzing data on soil characteristic measurements. Even though this approach enables the acquisition of detailed information, limited access to desertification areas and limited spatial coverage pose challenges. In contrast, detecting and characterizing large-scale desertification, remote sensing data is a cheap and efficient way of desertification monitoring and assessment [4]. Hence, studying the applications of remote sensing techniques in desertification monitoring is necessary.

Different methods, applications, platforms, and software have been developed as a result of numerous studies assessing desertification in past decades [5]. Collecting data efficiently and accurately over wide areas, applications of remote sensing methods and techniques in monitoring and assessing desertification have gained increasing popularity. Reviewing all studies related, past reviews mainly focused on comprehensive and systematic summaries of remote sensing-related indicators and methodologies in desertification monitoring and assessment [6]. However, they often failed to include a detailed analysis of specific applications. This review discusses major examples of remote sensing data acquisition, specific applications, and future prospects in detail by comparing and connecting different methods. In addition, analyzing the advantages and drawbacks of each methodology, this study includes development expectations and suggestions on remote sensing applications and desertification studies.

This study aims to prove the significance and necessity of applying remote sensing in desertification monitoring. In the beginning, this study introduces satellite images and unmanned aerial vehicle technology as two major access to remote sensing data. Then, this study discusses three applications of remote sensing and provides pros and cons for each application, including normalized difference vegetation index (NDVI), land cover classification, and SMA. At last, the study lists some future prospects for data acquisition methods, remote sensing techniques, and research topics.

2. Access to Remote Sensing Data

2.1. Satellites

The utilization of satellite systems by remote sensing techniques enables scientists to gain geological data from a distance. Orbiting the Earth at high altitudes, satellites collect data on the Earth's surface on a global scale through passive or active imaging. Satellites with passive sensor systems, including Landsat, Moderate-resolution Imaging Spectroradiometer (MODIS), and Sentinel, detect the natural radiation emitted or reflected by the ground without the need for an external source of radiation. Active imaging, in contrast, is a technique that involves actively illuminating a scene with some form of energy, such as light, sound, or radio waves, and then analyzing the reflected or scattered signals to create an image of the scene. Active imaging allows for improved resolution and accuracy compared to passive imaging techniques, particularly in low-light or low-visibility conditions.

Among satellite data for studies of desertification, Landsat images are the most commonly employed, due to Landsat's availability to a longer time frame that enables change detection analysis. MODIS and Sentinel satellites are also popular data sources [1].

2.2. Unmanned Aerial Vehicle Technology

Admittedly, remote sensing satellites enable data collection from a large region. However, due to satellites' susceptibility to interference, the atmosphere and clouds will easily affect our observation. In addition, the construction and manipulation of satellites cost a huge amount of money and labor. Thus, the discovery of another stable and cheap means to collect remote sensing data is necessary.

Unmanned aerial vehicles (UAVs), also known as drones, are increasingly used for obtaining remote sensing data in a variety of applications nowadays due to technological advancements. UAVs can be equipped with a range of sensors, including high-resolution cameras, thermal imaging cameras, LiDAR, and hyperspectral sensors. One major advantage of using UAVs for remote sensing is their ability to access targeted areas and fly at lower altitudes than satellites, providing higher-resolution imagery and more precise data [7]. At present, the maturity of UAV remote sensing is increasing dramatically. Overall, the versatility and flexibility of UAVs make them suitable complementation for satellite remote sensing.

3. The Application of Remote Sensing in Desertification Monitoring

3.1. NDVI

The application of the NDVI in monitoring land desertification has the greatest popularity among scientists [1]. NDVI is a remote sensing index that measures the vegetation cover and vegetation health of an area based on the difference between the reflectance of near-infrared (NIR) and red light. NDVI is calculated using equation (1):

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

As is shown in equation (1), NIR and R represent spectral reflectance (or radiance) measurements recorded with satellite sensors in near-infrared and visible red regions respectively [8]. This data can

be obtained easily using remote sensing techniques. According to satellite image data provided by Landsat 8, NDVI can be calculated using equation (2):

$$NDVI = \frac{Band\ 5 - Band\ 4}{Band\ 5 + Band\ 4} \quad (2)$$

As is shown in equation (2), Band 5 is the near-infrared band and Band 4 is the red band of Landsat 8 satellite images. Fig. 1 is an example of an NDVI map of Turpan, Xinjiang, China, shown using pseudo color based on Landsat data. Turpan is experiencing desertification and land degradation due to a loss of vegetation cover. As is shown in the figure, when red parts normally represent water bodies with negative NDVI, the orange regions can indicate desertification, as they have smaller NDVI values and less vegetation cover. In contrast, areas with green colors have denser and healthier vegetation.

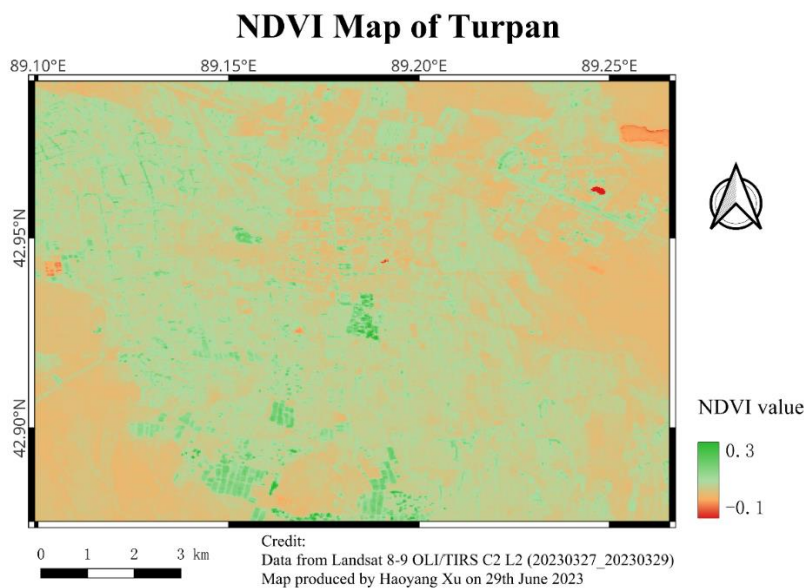


Figure 1. NDVI map of Turpan, Xinjiang, China. Orange areas indicate a higher possibility of desertification. Picture credit: Original

NDVI provides an accurate measure of vegetation cover, a key indicator of desertification. The range of NDVI values is -1 to 1, with positive values indicating healthy vegetation and negative values indicating bare soil, sand, or water bodies. Land degradation often occurs in areas with low NDVI values as a result of a lack of vegetation cover on the land surface. Regions where desertification is escalating or migrating can be tracked and monitored using temporal contrasts of the image. In comparison to traditional methods such as ground surveys, NDVI allows for rapid and objective assessment of vegetation cover over large areas. This is particularly important in arid and semi-arid regions where land cover vegetation varies greatly depending on the season and weather conditions, greatly improving the efficiency of relative investigations.

But there are also some potential drawbacks associated with the use of NDVI. Providing only information on vegetation cover, NDVI does not account for other factors that contribute to desertification, such as soil degradation, land-use change, and human activities, thus failing to provide a comprehensive picture of the status of desertification in an area. In addition, NDVI's disability to differentiate between different types of vegetation, such as shrubs or trees, leads to ignorance of changes in the composition or structure of vegetation, which can also be important indicators of desertification.

3.2. Land Cover Classification

Land cover classification refers to the process of identifying and mapping different types of land use, such as vegetation, water body, and human constructions, based on their spectral characteristics as observed from remote sensing data. This information is crucial for understanding landscape

patterns, tracking changes over time, and assessing the impact of various environmental stressors, including desertification. Land cover classification mainly uses multispectral and hyperspectral imaging that captures reflectance values across multiple bands of the electromagnetic spectrum. This technique enables experts to identify areas that are particularly vulnerable to desertification and prioritize conservation efforts accordingly. Development of targeted interventions aimed at reducing human impacts on specific areas and promotion of sustainable land use practices require mapping land cover types and assessing their vulnerability to desertification. In addition, land cover classification promotes the analysis of the impact of different environmental stressors on ecosystem health and resilience. For example, changes in land cover patterns may be indicative of soil degradation, nutrient depletion, or water scarcity, all of which can contribute to desertification. Tracking changes in vegetation patterns over time enables the identification of the underlying drivers of desertification and the development of strategies to mitigate their impact. Moreover, land cover classification can be used to assess the success of conservation and restoration efforts aimed at reducing desertification. Changes in vegetation patterns and the effectiveness of different interventions can be assessed and analyzed after comparison between recent land cover maps and historical data using the land cover change technique.

Satellite data provided by Landsat 8 is often applied to draw classification maps. After the creation of training inputs, machine learning algorithms can evaluate the properties of each pixel and distinguish between different categories based on data from different bands in the satellite images. Then, a whole classification map is generated. Fig. 2 is an example of a classification map of Turpan produced using machine learning techniques. In this figure, yellow represents sand, indicating a greater possibility of desertification. At the same time, the color black, blue, green, red, and brown each represent a different type of land cover. As a result, by comparing classification maps from different ages and producing land cover change maps, scientists gain a clearer understanding of the change tendency and the ability to predict and simulate future land cover conditions. Compared to the NDVI map (Fig. 1), the classification map (Fig. 2) presents similar results of desertification assessment while it provides extra information on land use distribution.

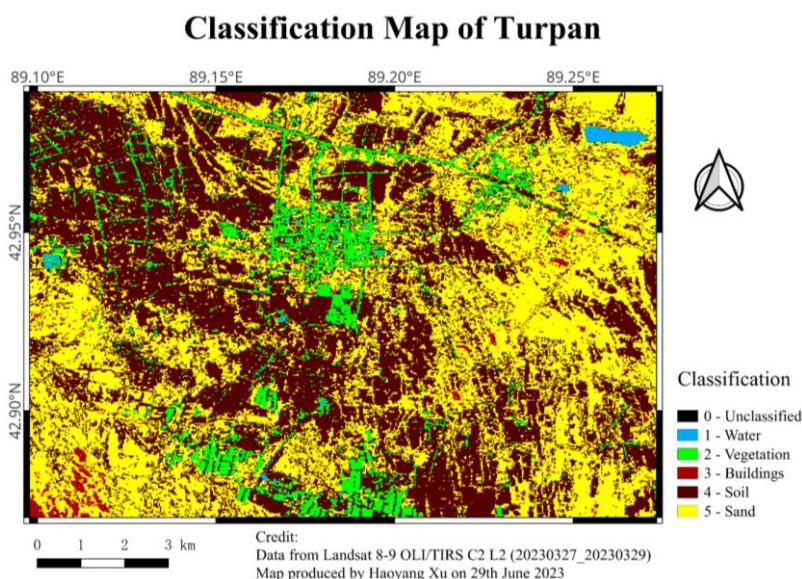


Figure 2. Land cover classification map of Turpan, Xinjiang, China. Yellow areas indicate a higher possibility of desertification. Picture credit: Original.

However, there are several challenges associated with using land cover classification for desertification monitoring. The need for accurate and up-to-date remote sensing data requires significant investment in technology and infrastructure, which may not always be feasible in regions with limited resources. The complex nature of land cover classification also makes it difficult to distinguish between different types of lands with similar appearances using remote sensing data alone.

Human expertise is often required to supplement automated classification algorithms, particularly in areas with heterogeneous land cover patterns or mixed-use landscapes.

3.3. SMA

While some statistical methods are usually applied in image classification, a precise measurement requires the pixel size to be tinier than the variability of the fundamental landscape components. However, the soil-plant canopy data can be separated using the sub-pixel method known as SMA to identify the relative soil, vegetation, and non-photosynthetic vegetation [9]. SMA assists in creating spectral signatures that can be transferred from scene to scene by distinguishing between spectrally similar elements, including distinct vegetation covers, certain water types, or distinctive buildings and other human constructions in rural locations [10].

Typically, there are three stages to perform SMA: i) determination of endmembers by evaluation of the dimensionality or quantity of distinctive reflecting materials in a landscape; ii) description of each of the pixel's endmember's physical nature; iii) estimation of the specific proportions of each endmember.

The expression of the Linear Mixing Model (LMM), the fundamental mathematic model applied in SMA is shown in equation (3)-(4):

$$Rp(\lambda) = \sum_k^n EM_{ik}f_{ik} + \varepsilon_i \quad (3)$$

$$\sum_k^n f_{ik} = 1 \quad (4)$$

As is shown in equation (3), $Rp(\lambda)$ represents each pixel's surface reflectance; EM_{ik} is the relative radiance for each endmember in band i ; f_{ik} represents the percentage of each endmember k ; k represents each of n endmembers; ε_i represents the residual between measured and modeled DN. The mixing proportions are considered to add up to one in equation (4) since the fractions of each endmember are assumed to be percentages [10].

While SMA provides a high level of detail when analyzing an image, allowing for more accurate identification of desertification phenomena, this technique is especially sensitive to noise in the data. In addition, SMA can be computationally intensive, requiring significant computing resources and time, creating a barrier to real-time monitoring and assessment of desertification.

4. Future Prospect

While the application of remote sensing in desertification monitoring has become openly and broadly researched, more needs to be done in the future [1]. Advances in remote sensing tools, such as the development of hyperspectral sensors, will allow the collection of more detailed information about environmental variables related to desertification. Collecting data at hundreds of narrow wavelength bands, future sensors will enable the identification of subtle differences in vegetation cover, soil moisture, and other parameters, developing more accurate models for predicting and managing desertification processes. Another promising research topic is the further applications of UAVs for data collection. While UAV technology is still under development, it has the potential to revolutionize desertification monitoring by providing real-time data on environmental changes at a local scale. As a result, targeted management strategies, such as precision agriculture and grazing management, can be developed to mitigate the effects of desertification.

While NDVI is currently a suitable and popular variable for desertification monitoring, detecting and monitoring desertification by simply considering one variable can cause invalid results and biased conclusions on desertification phenomena. Thus, more studies that use multiple variables to precisely identify desertification are encouraged. In addition, more advanced machine learning algorithms and artificial intelligence can be integrated with remote sensing techniques to help automate the analysis of large amounts of remote sensing data, which simplifies the process to classify land covers and identify changes over time and greatly improves the ability to monitor desertification on a larger scale. Moreover, prediction and simulation of future dynamics of desertification have been rarely discussed

so far. Due to the ongoing trend of climate change, more future studies should focus on the topic of desertification prediction to better monitor and protect lands from desertification [1].

5. Conclusion

The application of remote sensing in desertification monitoring has shown great promise in addressing one of the most pressing environmental challenges of our time. This study mainly introduces access to remote sensing data and the pros and cons of specific applications in desertification monitoring, including NDVI, land use classification, and SMA. Satellite images and UAV technology are two major sources of remote sensing data. NDVI measures the vegetation cover to reflect potential desertification but fails to offer a comprehensive picture of the desertification status of an area. While land cover classification identifies different types of land use to monitor desertification, track changes over time, and find potential environmental stressors, the technique requires huge investments in technology and labor. SMA, the sub-pixel classification technique, provides a detailed analysis while consuming significant computing resources and time. This study puts forward some suggestions for future developments of remote sensing technology in desertification monitoring. In the future, more accurate remote sensing data will be available due to the development of satellite sensors and UAV technology. Investigations of multiple variables, artificial intelligence-assisted analysis, and simulation of future desertification status will become promising techniques to improve the accuracy and efficiency of desertification monitoring with remote sensing.

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