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The use of remote sensing for desertification studies: A review☆

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ABSTRACT

The study and assessment of desertification and/or the advance or retreat of arid areas as a function of natural and anthropogenic causes is necessary for the prediction of future risks from climate change, and to support policymaking, action plans, and mitigation measures that can be taken at local and global scales. Remote sensing enables modelling, monitoring, and prediction of the behaviour of several elements of desertification. There have been numerous approaches to study desertification using remote sensing over the years. This research explored the timeline and global distribution of studies using remote sensing in studying desertification. Additionally, the review evaluated the key methods and variables that have been used to study desertification from remote sensing data.

The use of remote sensing for desertification studies can be trace back to 1991. From 2015 to 2020, more than 40 articles were published per year, showing that there has been a recent increase in the use of remote sensing techniques and its availability for monitoring desertification. Most regions of the world affected by desertification are being studied using remote sensing, however, there is a marked geographical variation between the number of studies in various regions, with Asia having disproportionately high number of studies compared to America or Africa. The country with most studies of desertification using remote sensing is China.

In terms of satellite data, Landsat images provide the bulk of data used to study desertification, especially the Thematic Mapper (TM) sensor. Classification and change detection are the most used methods to study desertification from remote sensing data. Additionally, land cover/land use change and vegetation and its attributes (e.g., Normalized Difference Vegetation Index - NDVI) are the most used variables to study desertification using remote sensing techniques. Finally, the review found major differences in terms of the ranges or thresholds applied to these variables when determining the presence or risk of desertification. Therefore, there is a need to develop thresholds and ranges of changes of key selected variables, which can be used to determine the presence of desertification.

1. Introduction

Desertification and land degradation has a significant economic and environmental impact. It is estimated that globally, around 1.4 billion people are affected by land degradation, of which 74% are poor people. Additionally, drought and desertification are leading to an annual loss of 12 million hectares of arable land (United Nations, 2015).

Land degradation refers to loss of the biological or economic productivity of any land resulting in deterioration of physical, biological and/or economic properties of soil, and long-term loss of natural vegetation (United Nations, 1994; Bakr et al., 2012; Van den Elsen and Jetten, 2015). Since 1970, political and international interest over this phenomenon has increased, specially over arid, semi-arid and sub humid ecosystems, due to their significant role in food production and social development of communities (Li et al., 2016; Becerril-Piña et al., 2016; Liu et al., 2018; Zhao et al., 2018).

Land degradation occurring in arid, semi-arid and sub-humid ecosystems is often referred to as desertification. Desertification can be defined simply as "the making of the desert" or "the production of desert conditions" (Verstraete, 1986). However, the United Nation gave the first comprehensive definition of the term in 1977, which took into consideration the economic impacts of this phenomenon. It defined desertification as "the diminution or destruction of biological potential of land which can lead to ultimately to desert-like conditions" (United Nations, 1977). This definition was modified in 1994, when desertification was defined as "Land degradation in arid, semi-arid, and dry

☆ All 384 filtered documents were examined to determine.

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sub-humid areas resulting from human activities and climate variation", including the human effects on climate variation beyond the economic loss (United Nations, 1994). This last definition has been formally and widely used, since then, for multiple studies on desertification around the world, thus providing multiple and variable scopes on how to measure, analyse, and model measure desertification. (Kassas, 1995; Li et al., 2006; Cui et al., 2011; Bakr et al., 2012; Lamchin et al., 2016; Liu et al., 2018; Xu et al., 2016; Becerril-Piña et al., 2016; Zhao et al., 2018). Taking into consideration these definitions, for this study, we adopt the definition of desertification as: "land degradation in arid, semi-arid, and dry sub-humid areas resulting from human activities and climate variation which can lead to desert-like conditions".

Desertification has been recognised as one of the biggest concerns for the international community given the many environmental problems associated with it such as soil degradation, soil salinization, silting and dust storms (United Nations, 2015). In addition, desertification can lead to some significant social-economic problems such as food shortage, poverty, and health problems (e.g., malnutrition to respiratory problems) (Xiao et al., 2006; United Nations, 2015). Desertification is considered as an irreversible process driven by natural factors such as temperature, precipitation, loss of vegetation cover, and human factors such as land use/land cover change, industrialisation, and urbanisation (Stringer, 2008; Santini et al., 2010; De Pina Tavares et al., 2015; Xu et al., 2016). Environmental and social problems caused by desertification have become one of the key factors preventing sustainable development in arid, semi-arid and sub humid areas (Li et al., 2016; Helldén and Tottrup, 2008; Wang et al., 2006). Recognising the potential impacts of desertification on economy, environment, and society, to combat desertification, it was included as one of the Sustainable Development Goals of the 2030 Agenda for Sustainable Development. The Sustainable Development Goal 15 aims to *"protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss"* (United Nations, 2015). Target 15.3 of the sustainable goals, declares to restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation-neutral world by 2030. Combating desertification is crucial to the reduction of global poverty as well as to the mitigation of biodiversity loss and human induced global climate change.

Future climate change scenarios that predict how temperature, precipitation, carbon sequestration and atmospheric carbon dioxide accumulation will impact desertification, show an exacerbation in the progression of desertification worldwide, through precipitation variability, increased drought frequency and persistence of dry conditions (D'Odorico et al., 2013; Al-Bakri et al., 2016; Mutti et al., 2020). Given the fact that desertification is caused by natural and anthropogenic factors, the prediction of future trends in desertification is focused on these factors including temperature, precipitation, wind, and vegetation covers/types. The accepted premise is that rising temperatures and decrease in precipitation will aggravate or increase the presence, development, and maintenance of droughts. This will affect vegetation growth, leading any area to a natural desertification process that will hardly be reversed (Xue-Yong et al., 2002). On the other hand, anthropogenic factors that lead to desertification are related to population increase and urbanization processes. Agriculture can become a factor if overgrazing, over-cultivation, and/or any practice related to over-exploitation of land or soil is taken over an extended period (Kassas, 1995; Portnon and Safriel, 2004; Salvati and Bajocco, 2011).

The definition of desertification given by the United Nations in 1994, and used widely since then, open the doors to multiple ways to undertake the assessment of the desertification phenomenon (Verón et al., 2018). This is due to the number of factors that can lead to desertification according to this definition. Countries experiencing desertification might select different variables to determine its occurrence, and the thresholds for such variables that determine the presence or absence of desertification. These differences make it hard to compare and select appropriate variables to study desertification, and, more importantly, there are differences on what changes determine the risks of desertification and when it can be considered irreversible (Wang et al., 2006; Li et al., 2016). The study and assessment of the desertification process and/or the advance or retreat of arid areas as a function of natural and anthropogenic causes is necessary for the prediction of future risk posed by climate change, and to rightly support the policymaking, action plans, and mitigation measures that can be taken at local and global scale (Kassas, 1995; Odjugo and Ikhijoria, 2003; Xu et al., 2016). The establishments of monitoring programs are the most effective way to assess desertification processes as it helps to understand the mechanisms and changes of this ecosystem before they become irreversible (Zhao et al., 2018; D'Odorico et al., 2013; Xiao et al., 2006).

Understanding the desertification process and its impact mostly rely on analysing longer term data on soil characteristic measurements (e.g., humidity, soil moisture, organic soil width), and agricultural production (e.g., from local farmers surveys and/or interviews) (Solomun et al., 2018). Even though this approach allows for detailed understanding of the physical processes that may lead to desertification, it is limited in terms of spatial coverage. Moreover, in many arid and semi-arid regions, limited access to calibrated field equipment and expertise to collect longer term data pose additional challenges for ground-based monitoring. Therefore, remote sensing data, in particular those from Earth Observation satellites has been used as an alternative tool to study desertification. With the ability to provide enhanced spatial and temporal coverage, remote sensing data allows exploration of desertification at local to global scale over time (Tueller, 1987).

The study of desertification using remote sensing techniques goes back to 1981 when Ulf Hellden studied approaches for rehabilitating degraded ecosystems in Africa (Helldén, 1981). Since then, there has been numerous studies that assess desertification (D'Odorico et al., 2013). Consequently, different platforms, satellites, software, and methods had been developed. Remote sensing methods and techniques can collect data rapidly and reliably over wide areas and has been applied to monitor and assess desertification and its dynamic processes. Changes in vegetation and land cover/land use are the most common indicators used in many studies to monitor desertification. Generally, changes in vegetation cover are used as the most direct indicator to reflect the dynamic processes of desertification (Huang et al., 2017; Liu et al., 2018).

The purpose of this research is to understand how remote sensing has been used to study desertification. A systematic review of research journal articles was made. It aimed to set a timeline of the use of remote sensing to study desertification, how its use has evolved through time and the geographical distribution of these studies. This systematic review also focusses on evaluation of the objectives or purposes of remote sensing-based desertification research and an identification of the methods and variables used over time to understand desertification process and its impact.

2. Method

For the purposes of this research a systematic review was undertaken. A systematic review is defined as an evidence-based review on multiples questions about a study area or topic, made to identify and critique relevant research and to analyse data from multiple studies. Additionally, a systematic review should be replicable and demonstrate the effects, interventions, and gaps of knowledge about the topic researched (Centre for Reviews and Dissemination, 2009).

A literature search was carried for every publication available from 1960 up to 23rd of February 2021 in two scientific databases: Scopus and Web of Sciences. These two databases were selected because they contain most of scientific publications and they are rigours. The search was conducted using the following criteria:

- "Desertification" **OR** "Land Degradation" **AND** "Remote Sensing" **OR** "Satellite Data", must appear in the following fields: article title, abstract, keywords, source.
- The articles included must be between 1960 and 2021, using all the span of the databases. This considering that Web of Science have a time search for "Publication date" that goes back to 1970, and SCOPUS to 1960.
- Only English language publication.
- Only peer review primary research journal articles are considered.

The search of journal articles using the previous criteria resulted in a total of 8235 documents between both databases on desertification studies that use remote sensing or satellite data as a source or technique to analyse, characterize or evaluate the phenomenon or generate new methods and/or variables for desertification.

As a first filter, all duplicated documents were removed, leaving 7534 documents. Following on, only documents that had "desertification" and "remote sensing"/"satellite data", or the mention of specific platforms or sensors, mentioned directly in the title or in the abstract were selected, ensuring that the resulting documents had "desertification" as one of the key objectives of the article, and guaranteeing that the study was made using remote sensing data. This first filter narrowed the database to 791 documents.

The second filter looked to identify the articles that treated "desertification" as the prime research purpose or objective, constituting desertification as the result itself of the published research. For this, abstract sections and, in some cases, introductions and conclusions of the articles were reviewed, giving a refined list of 518 documents that study desertification using remote sensing.

The third filter considered the availability of the documents, in digital or physical form. From this filter, 452 articles were found digitally, with the first being from 1986 (i.e., Barrett E.C., Hamilton M.G. (1986) "Potentialities and problems of satellite remote sensing with special reference to arid and semiarid regions").

With all documents available for review, a final filter was applied considering language (for example, to remove articles that had the abstract in English but the article itself was in Chinese, Portuguese, or French), and duplicated documents that passed the first filter (given typos in the title or differences in the order of the authors). Finally, review articles were filtered out as this systematic review only focused on primary research. This resulted in a final of 384 articles available for this research to be reviewed (Fig. 1).

a) Since when has remote sensing been used to study desertification.
b) Where is desertification being studied using remote sensing?
c) Which satellite data is being used to study desertification?
d) What is the purpose of the study of desertification using remote sensing?
e) Which are the most used variables to study desertification using remote sensing?
f) What method/s are being used to study desertification using remote sensing?

3. Results

The initial search yielded a total of 8235 documents. This were filtered down to 384 articles following the process described in the methods section. The 384 articles were then classified to address the questions mentioned in previous sections.

3.1. Temporal evolution of the study of desertification using remote sensing

From 1986 to 1990, most articles found were reviews on the advantages, disadvantages, and uses of remote sensing to monitor arid areas and the "newly" discovered desertification phenomenon. These literature reviews were dedicated to show the potentialities of using satellite data to study desertification. For example, Barrett and Hamilton (1986), sought to understand the present and future roles of remote sensing for observation, management, and control of dryland environments, and how to capitalize on the attributes of satellites to advance the knowledge on arid zones. Tueller(1987), considered the potentialities of studying arid areas, giving their characteristics (e.g., cloud-free weather, high air temperature), using remote sensing, while at the same time

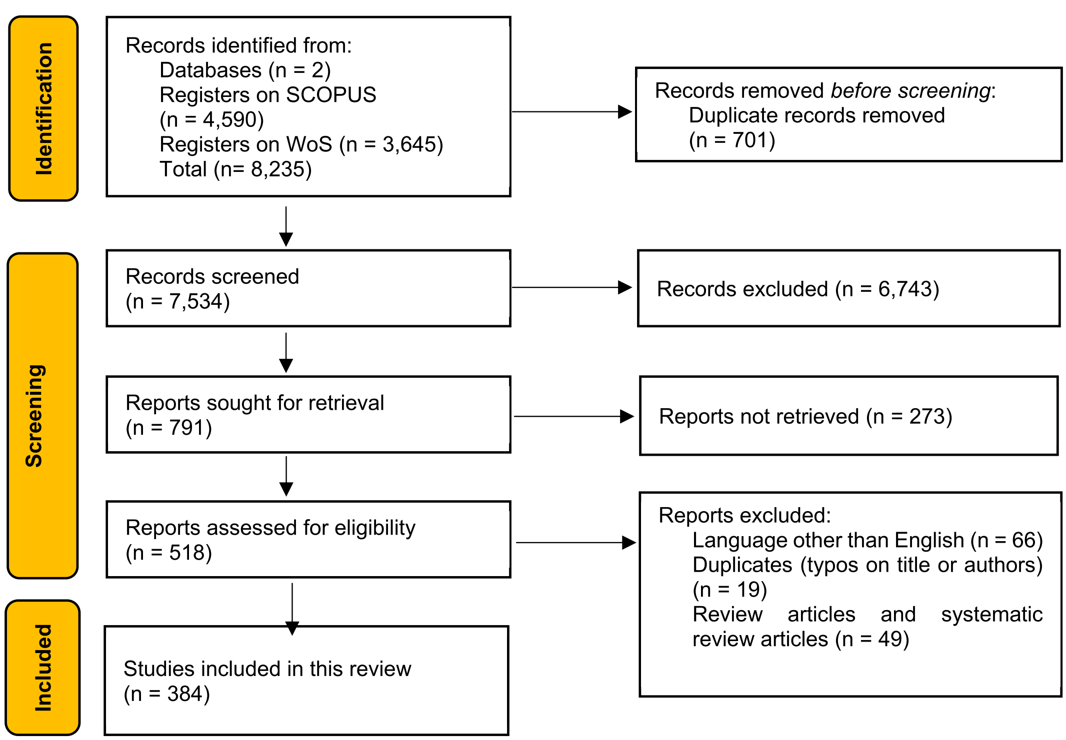

Fig. 1. Results and filtering process of articles that comply with the search keywords used.

setting out challenges to study it from a scientific and management point of view. Similar to Barrett and Hamilton (1986), Tueller (1987) also explored the advances in remote sensing technologies and the different scales that allowed it to be used to explore the arid lands in its full scale. Both pointed out the potentialities of using remote sensing and its applications in arid environments and concluded that it is a useful technique/tool for studying arid lands.

It is in 1991 when the first record of primary research focused on desertification using satellite data appears in the filtered catalogue. This study used Normalize Difference Vegetation Index (NDVI) measurements obtained from the National Oceanic and Atmospheric Administration Advance Very High-Resolution Radiometer (NOAA/AVHRR) and its relationship with rainfall gradients to analyse the vegetation production to determine desertification presence and associated risk to the deep well areas in the Senegalese side of the Sahel (Hanan et al., 1991). Hellden in the same year conducted a study in the Sudan side of the Sahel region to analyse NDVI trends, obtained also from NOAA/AVHRR, from 1981 to 1987 and compare his results with other research and results on the same area They established the need of a scientific based assessment of desertification, given on the lack of field data in the area and of the topic itself (Helldén, 1991).

Since then, there has been a significant increase in the number of articles studying desertification using remote sensing data. Between 2000 and 2010 on average 10 articles were published which utilised remote sensing data, a number that has significantly increased since 2015 to almost 40 articles per year. This indicates an increase in the use of remote sensing techniques and its availability for monitoring desertification (Fig. 2).

3.2. Global distribution of desertification studies using remote sensing

Forty-eight countries were found in the 384 articles where desertification has been studied using remote sensing. China is the most studied country, with a regular and consistent number of studies of desertification using remote sensing from 1999 to 2021, with a total of 177 articles covering this period. There are a total of 16 countries in Asia where desertification was monitored using remote sensing, but by far China is the most studied country.

The map in Fig. 3, reflects arid areas where remote sensing has been used to study desertification, however, there is a marked geographical variation. This difference can be seen, for example, between the number of studies of desertification in Asia compared with the study of desertification in America or Africa. The number of articles on desertification studies using remote sensing in Africa is 45 articles and 35 in America, in comparison Asia has 245 articles on desertification using remote sensing. This can be seen as a geographical gap in terms of where desertification is being studied, or as an opportunity to see the developed methods, used variables and different results obtained in this continent, and how those can be interpreted in terms of public policy and governmental strategies over this phenomenon that encourage the continuous study of desertification.

There are several regional studies that include more than one country, such as the Sahel, which is studied in 9 articles, especially the areas of this region in Senegal, Mali, Niger, and Burkina Faso. The Mediterranean area is the most studied region in Europe, with 7 articles. There are also studies that take a bigger scale, such as continents (Africa, Asia, Europe) or parts of them (Central Asia, West Africa, Iberian Peninsula). 7 articles were found on world studies, considered as studies on a global scale of variables or behaviour of arid areas.

In Africa, desertification has been studied in 17 countries, with Morocco being the focus of most articles (10 articles). In America, desertification has been studied in 6 countries, with Argentina having the most studies (13 articles). In Europe desertification has been studied in 9 countries, with Spain having the most articles (6 articles). A full list of countries and regions is detailed in appendix A.

3.3. Satellite data used to study desertification

Landsat images are the most used satellite data for studies of desertification found in this research, mostly due to the access to a longer time frame that allows change detection analysis. The second most used satellite data is data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard Terra and Aqua satellites (Fig. 4).

Even though the first paper that mentioned the use of remote sensing in studying desertification was in 1986 (i.e., Barrett and Hamilton, 1986), this study was a review on the potential of its use. The first paper that used satellite data to study desertification can be traced back to 1991. The study by Hanan et al. (1991) used satellite data to estimate desertification in Senegal using the National Oceanic and Atmospheric Administration Advanced Very High-Resolution Radiometer sensor (NOAA/AVHRR).

In 1993, NOAA/AVHRR, Falcon 20 and DC-8 radar images were used in two different studies, the first for a global scale study of the desertification phenomenon that aimed to establish changes on different arid areas, using multiple platforms, sensors, and products to obtain a higher temporal resolution (Randolph., et al., 1993). The second study was carried out in Spain for the creation of the prototype that now is known as the Mediterranean desertification and land use project (MEDALUS), based on the calculation of different quality index that measure the

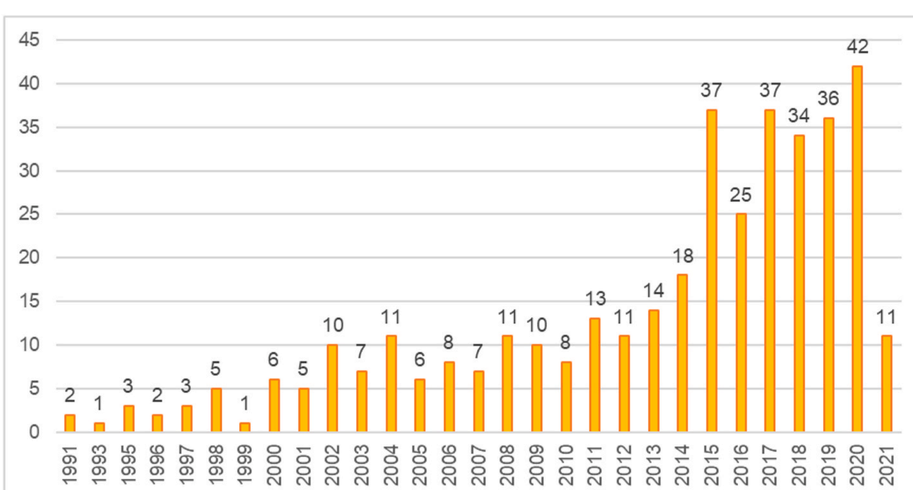

Fig. 2. Timeline of the use of remote sensing to study desertification.

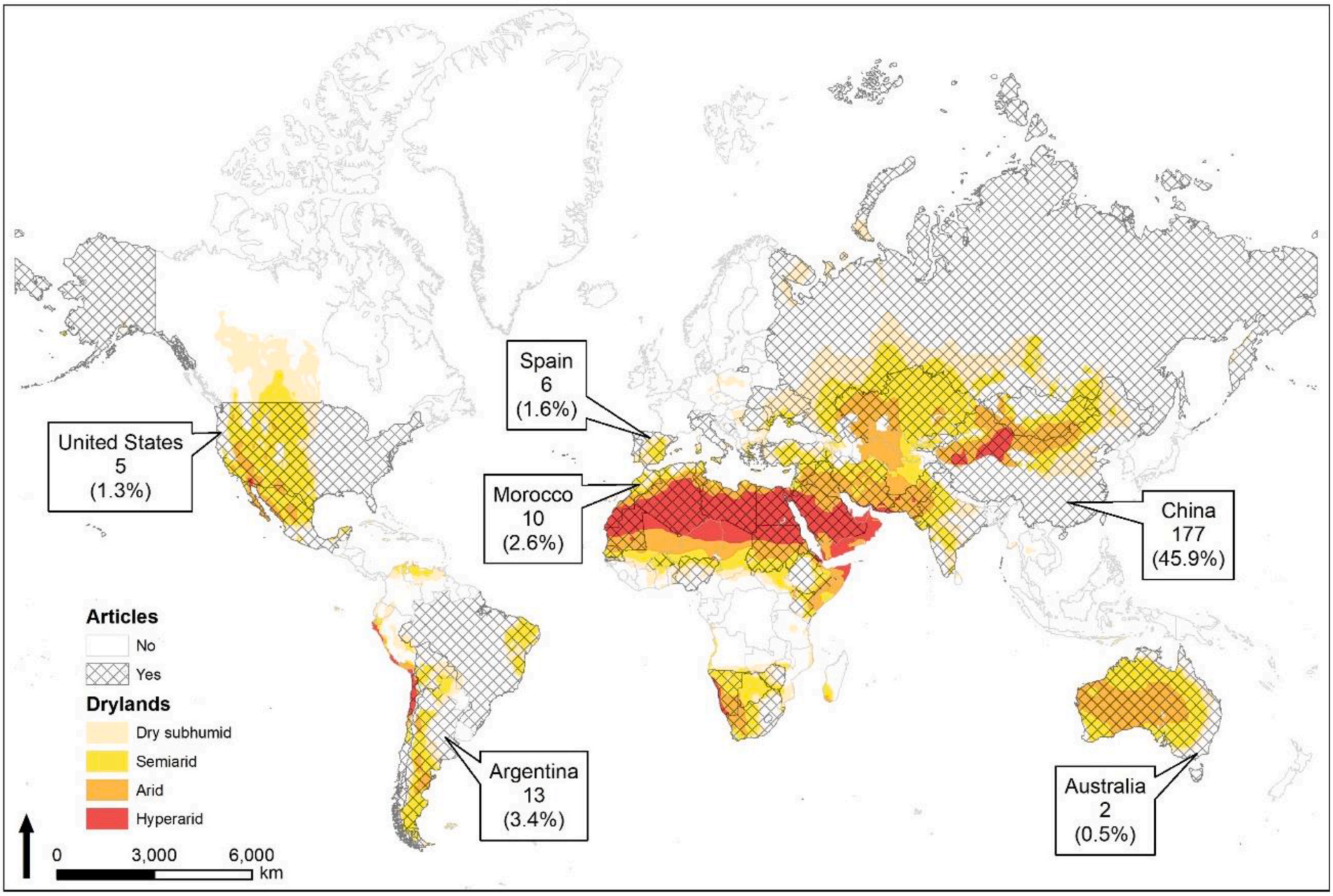

Fig. 3. Countries and regions with research articles on desertification using remote sensing.

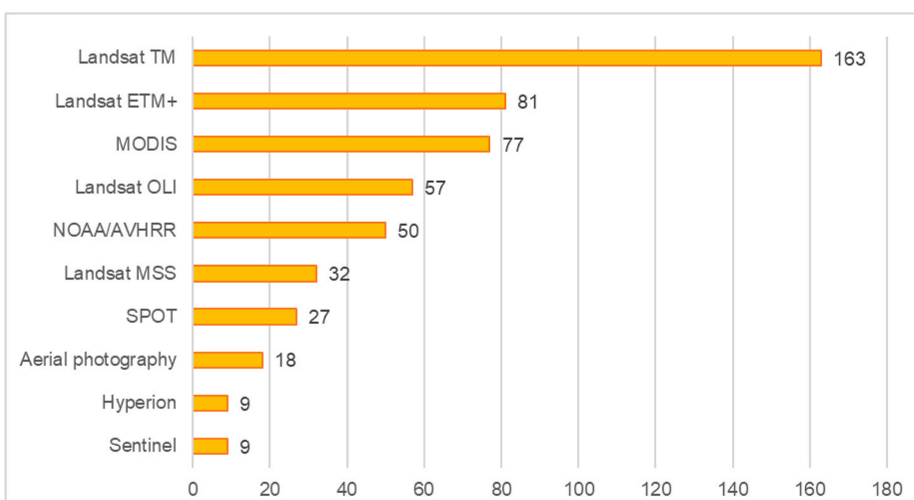

Fig. 4. Most used satellite data in the study of desertification in the past 35 years.

impacts on vegetation, soil, climate, and human aspects of the desertification and aridification phenomena (Bolle et al., 1993).

The use of Landsat images to study desertification can be traced back to 1996 (Mohammed et al., 1996). Since then, it is the most used satellite data. Landsat Thematic Mapper (TM) sensor is the most used sensor for desertification studies (163 articles used data from this sensor). Additionally, the use of Landsat sensors is consistent over time, being used from 1996 to 2021.

Another satellite whose data is most used to study desertification is the MODIS Terra and Aqua Satellites, with 77 publications. The third most used sensor is the NOAA/AVHRR platform, with 50 publications. The studies using NOAA/AVHRR data are mostly focused on vegetation cover dynamics and land cover change.

Finally, it is worth to mention aerial photography. The use of this technique was found in 18 articles, with studies that went back to 1959 to detect changes over different landscapes overt time. It was also found that the use of these products was in conjunction with satellite imagery for the construction of the times series. Only two articles used aerial photography alone, considering an aerophotogrametric survey and a vegetation analysis to study desertification.

3.4. Purpose of the studies of desertification using remote sensing

Multiple objectives were found on the use of remote sensing to study desertification. Considering the similarity of those objectives, the results were classified in four classes. The classification of the objectives or purposes was made taking definitions of the principal category of each class, and their synonyms (Fig. 5).

The first group of studies were categorised as those that aimed to make a "Temporal analysis of desertification". These articles presented studies about desertification over time, some of them made a comparison over time of variables that helps to understand changes occurring in the different study areas. This class contains most of the articles of the reviewed catalogue (273) (Fig. 6). In general, "assessment" and "analysis" are the most common objectives found in this class. The most used method in this class was change detection, followed by classification for the analysis of trends, while the most used variable is land use and land cover, followed by spectral vegetation indices.

The second group of articles focused on "Quantification of the desertification process", which contains 23 articles that study specific condition on a specific year and/or month, which refers to a description of the process with the conditions and variables from that specific moment of time. Thus, it is a description of current conditions of the desertification phenomenon. In this sense there are fewer documents that establish present conditions of desertification (23 articles), and much more dedicated to establishing changes over time (273 articles).

The class "Identification of methods and variables" is the second majority group with 76 articles. This class recognise new variables and new methods for studying desertification. Just like the "temporal analysis of desertification" class, for "identification of methods and variables", change detection is the most used method. In terms of variables, vegetation cover or types of vegetation cover is the most used in this group.

Most of the documents presented the objective of temporal analysis of desertification (71%: 273 articles) (Fig. 6). At the same time, the articles in this catalogue did not present a sole objective More that 15% have two or three of the classes used in this study to classify the articles found (54 articles), with the "identification of variables or methods" and the "temporal analysis of desertification" the most common combination found in at least 22 articles (Fig. 7).

Beyond the analysis or assessment of current condition or historical evolution, few studies focused on the impact and analysis of future climate scenarios on desertification and therefore, these were grouped in the "Prediction and future simulation" class. A total of 12 articles were found to report predictions over the occurrence of desertification, or its risks to the years 2050 and 2100. This shows that the temporal analysis and/or quantification of desertification in current or past scenarios are the focus in the study of desertification using remote sensing over the prediction of its behaviour in future scenarios.

3.5. Variables used in the study of desertification

Given the various definitions of desertification, there are multiple variables that have been used to study desertification using remote sensing. Although over 164 variables were found that were used to study desertification, the most used variables are vegetation and land use and land cover change. The key variables are listed in Fig. 8. The first use of changes in vegetation cover as a variable to study desertification can be traced back to 1990 when Schlesinger studied the biological feedback to evaluate the aridification process as a result of long-term overgrazing (Schlesinger et al., 1990). In the following years, the use of vegetation as a variable, focused on the use of spectral indices for its measurement, and these vegetation indices have become the most used variable in the study of desertification. The indices have been used to study changes in agriculture, soil composition and land cover caused by desertification. Adding to that, the study of vegetation associated to desertification processes is usually accompanied by the study of changes in precipitation and temperature. This combination proved important, for example, in understanding the relation between climate variation and soil composition (Bolle et al., 1993; Mariano et al., 2018).

Some variables presented in Fig. 8 are presented as a generalization. Variables such as "Soil", comprises the use of different measurements like soil salinization, soil moisture, soil quality index, Top Grain Soil Index (TGSI). In the same line, the variable "Climate" is presented in different forms, such as the use of climate scenarios, climate quality index. Also, it is necessary to state that not all the variables listed in Fig. 9 are measured with remote sensing products or instruments, variables such as "Meteorological ground station data", are used for statistical analysis at local scale and/or for data validation of remote sensing obtained data (Lamchin et al., 2016).

The minimum number of variables used in studying desertification was 1, mostly focused on changes in vegetation cover over time on a specific study area or at global scale. The maximum combination of variables used were 9, indicating a vast possibility to establish relations between multiple variables to understand the desertification phenomenon (Fig. 9).

Considering the multiple variables found, and how they are used both individually and in combination, provides evidence on the fact that there are multiple ways to assess, measure, analyse, evaluate, and identify the occurrence of desertification. This can be considered as a limitation, as it points to a lack of international agreement and standardisation on the study, detection, and mitigation of the desertification phenomenon.

In summary, the most used variables found for the analysis, assessment, or evaluation of the desertification phenomena are NDVI, precipitation, vegetation (cover, type), soil and land use and land cover (LULC).

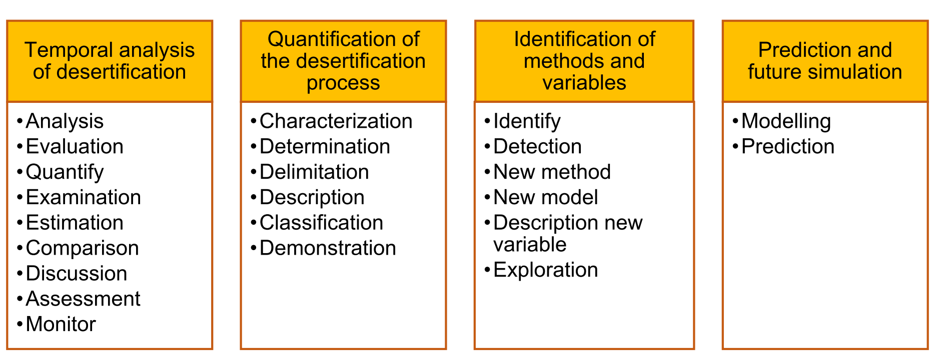

Fig. 5. Classification of the purposes to study desertification using remote sensing found in the filtered documents.

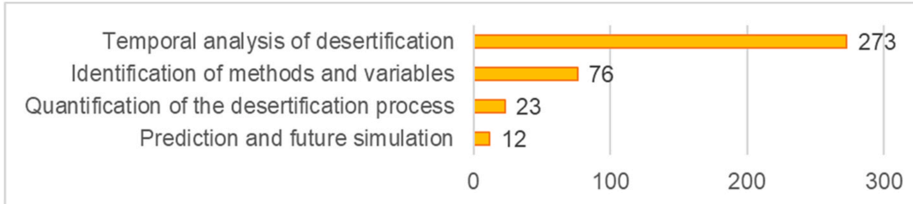

Fig. 6. Number of articles per class according to the purpose (s) to study desertification using remote sensing.

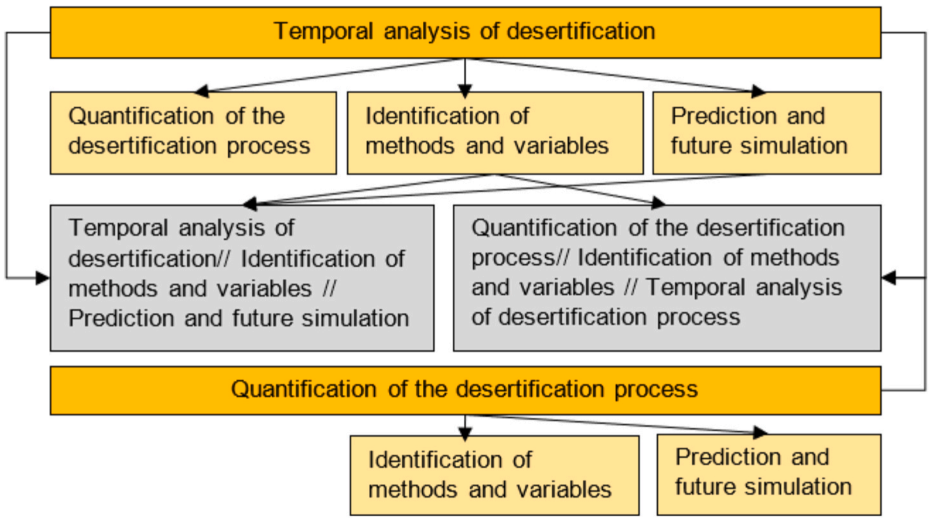

Fig. 7. Relationship between the classes that define the purpose of the study of desertification using remote sensing.

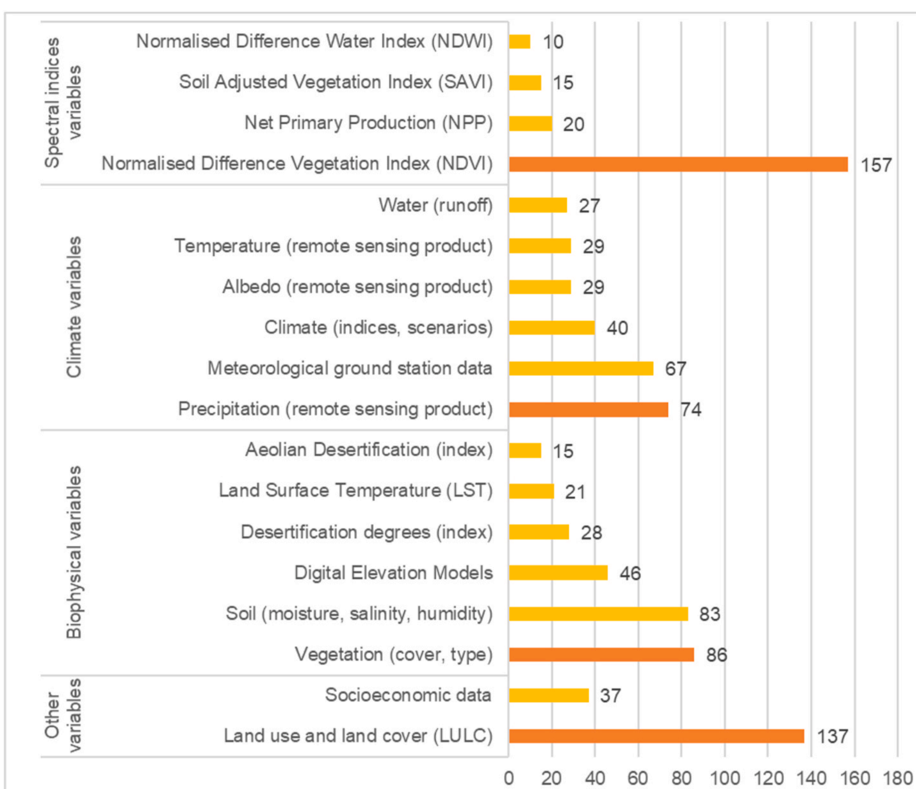

Fig. 8. Most used variables in the study of desertification using remote sensing.

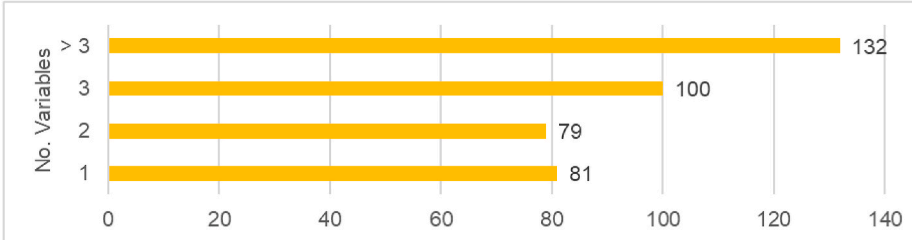

Fig. 9. Number of variables used to study desertification using remote sensing.

3.6. Methods used in the study of desertification

Since 1990, different methods have been used to study desertification using remote sensing data. Schlesinger et al., 1990, studied the biological feedback of global desertification in a study area in USA affected by long-term overgrazing practices. By 1991, the first Geographical Information System (GIS) based model to estimate the desertification state in Senegal was created (Hanan et al., 1991). Overall, classification and change detection, with 97 and 96 articles, respectively, are the most used methods to analyse and evaluate the process of desertification (Fig. 10).

From 1993, remote sensing measurements, inspection and mapping using different satellite image products were made. For example, Bolle et al. (1993), used 4 datasets – Falcon-20, radar images DC-8 and D-128 and ER-2 - with cross validation using meteorological station, specifically rainfall data, to measure an ideal drying period in Spain. The results show the use of field measurements and ground truth data in at least 93 articles (Bolle et al., 1993).

Change detection has been used to study desertification since 1995 and was the main method in 96 articles. Time series and its relationship with change detection started to be used as a method to predict the risk of desertification in New Mexico (Peters et al., 1997), and subsequently used in 28 articles.

Statistical metrics such as regression or correlation, were found in at least 56 articles on desertification using remote sensing, are mostly used to understand the relation between physical and anthropological variables and to analyse changes in the magnitude of the variables. For example, Runnstrom (2000), studied changes of NDVI and biological productivity in the grassland pastoral zones of China, over 10 years, as a result of the application of new policies about production and reclamation of land, affected by desertification, for pastoral and agricultural uses.

Time series-based analysis were found in 41 articles. In general, the authors analysed at least 15 years of continuous data or considered the same temporal difference between images for the analysis of their behaviour over time. For example, Xie et al. (2009), reconstructed the oasis development in the Manqin Basin in China, using archaeological and remote sensing data to understand the distribution of the oasis and changes on its structure caused by desertification.

Like Fig. 7, which shows the multiple interrelation between the purposes to study desertification using remote sensing, the methods listed in Fig. 10 are a report of the number of times the specific method is mentioned in the filtered catalogue of 384 articles that use remote sensing to study desertification.

4. Discussion

Results shows a timeline of research utilising remote sensing to study desertification that began in 1991 with less than 5 articles per year up to the year 2000. Since then, an average of 10 articles had been published per year. It is until 2015 when there was a significant increase to more than 40 publications per year. This indicates that, what started as a description of potential and advantages on the use of remote sensing to study arid areas, has become an established tool to study desertification primarily due to better access to satellite data.

There is a significant difference in the number and distribution of the location of studies using remote sensing to study desertification across the world. More studies were located in Asia than America and Africa. In general, studies of desertification using remote sensing were found in over 48 countries, with China being the most studied country. This represents an imbalance in the global distribution of desertification studies that use remote sensing data, which may skew the global community's understanding of desertification and its dynamics and hence the ability to produce policies to address desertification across the

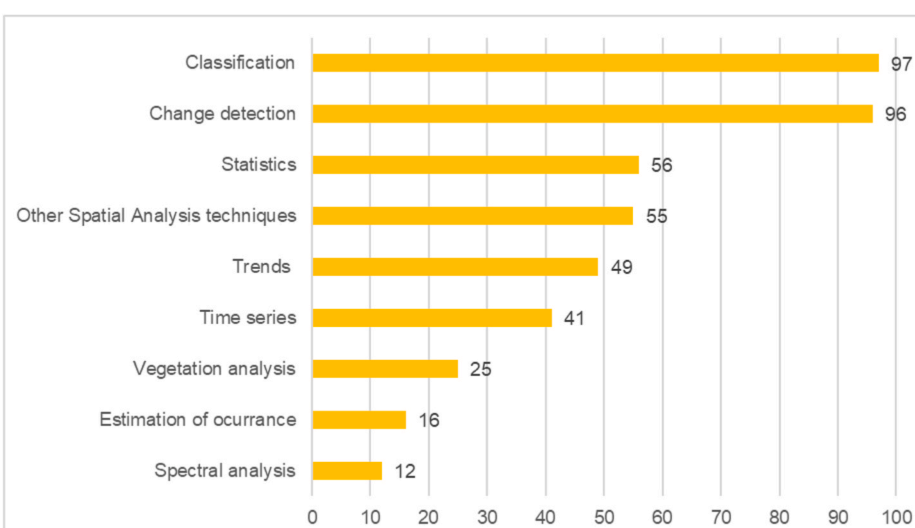

Fig. 10. Most used methods for the study of desertification using remote sensing over the past 35 years.

world.

For the study of desertification, more than 30 satellite platforms that provide different types of images on different spatial and temporal resolutions were utilised. The most used platform is Landsat, especially the Thematic Mapper sensors, which provide a longer and more accessible time range (1982–2013), allowing to perform multiple assessment and change detection analysis. Relatively new platforms such as Sentinel, gives access to high resolution images with pixel size of up to 10 m, but with reduced long term data availability, considering that the program was launched in 2014. However, they offer an opportunity to improve the analysis of different variables at higher spatial and temporal resolution when assessing desertification (Randolph et al., 1993; Kulik et al., 2020).

In terms of objective and purpose of study, prediction or future simulations of desertification using remote sensing data was the least explored objective. However, there is some progress being made in this area as exemplified by 3 articles on this topic appearing between 2016 and 2019. Future climate change scenarios are expected to exacerbate the progression of desertification worldwide, through precipitation variability, increased drought frequency and persistence of dry conditions (D'Odorico et al., 2013). Therefore, it is surprising that there are few studies dedicated to simulating future changes in desertification condition that use remote sensing data as a source or input, considering, for example, the advances made in land cover studies where remote sensing is being used to model changes over time (Land cover product of ESRI, or the Global Human Settlement (GHS), made via Sentinel-2 images; https://ghsl.jrc.ec.europa.eu/datasets.php, both produced via Sentinel-2 images). Most studies identified in this review are mostly dealing with past and present dynamics of desertification. To achieve sustainable development goals, studies which focus on future dynamics of desertification are needed.

The general causes of desertification (both natural and anthropogenic) have been determined and studied. In general, desertification is a long-term process, and can be produced, induced, and driven by multiple factors. According to the results obtained in this review, there is a general agreement on the variables used when studying desertification, with the most used being land use and land cover, Normalized Difference Vegetation Index (NDVI), precipitation, and other attributes of vegetation, such as cover, types, and phenology. Each one of the variables found in this review that can be used to study desertification can provide an individual perspective over changes in the surface of the earth and can explain to the process of desertification in diverse ways. Desertification itself is a long-term phenomenon that produce changes over time. In practical terms, desertification is produced over an extended period of drought that affect vegetation growth and development (D'Odorico et al., 2013; Al-Bakri et al., 2016; Mutti et al., 2020). Changes on vegetation distribution can be, as stated before, climate induced or human induced. Therefore, changes on the types of land cover and land cover use and socioeconomic structures can provide evidence on changes that can induce or maintain drought conditions. For example, extension of urban areas or changes on public policies over irrigation system on agriculture can affect climate conditions on a short to medium-term basis (Runnstrom, 2000).

Given that, the existing and most used definition of desertification does not determine the variables to use, in practical terms all of them can be used to assess desertification, but there are some limitations associated with each variable. For example, many of the reviewed articles used meteorological station data that can be traced back to 1950. However, not all the countries that are affected by desertification have meteorological data going back to the 1950s, limiting the time series to be analysed. This can result in the data not being used or if used, only few years can be assessed which can result in showing minimum or no changes in the landscape between the years.

According to the results obtained in this review, classification, change detection, and trend analysis are the most used methods to study desertification using remote sensing. In terms of classification, algorithms such as maximum likelihood or spectral mixture were principally used to classify land cover types before evaluating the process of desertification. Most of the change detection and trend analysis studies of desertification were based on a 15-year period.

Table 1
Comparison on variables and thresholds used to determine the presence or risk of desertification.

Variable	Author	Range
NDVI	Y. Julien et al., 2011	NDVI <0.2 Bare soil 0.2 < NDVI >0.5 combination Bare soil with Vegetation NDVI >0.5 Vegetation only
	Tereshchenko et al., 2012	NDVI = 0.219 (limit between arid and semiarid) NDVI = 0.323 (limit between semiarid and sub-humid)
	Bezerra et al., 2020	NDVI <0.101 Strong NDVI <0.145 Moderately 0.145 < NDVI <0.215 Slightly 0.215 < NDVI <0.315 Weakly NDVI <0.315 Non
	Lamchin et al., 2016	NDVI <0.25 Severe NDVI >0.40 Low 0.25 < NDVI <0.40 Medium 0.15 < NDVI <0.25 High NDVI <0.50 Non
Vegetation coverage	Fan et al., 2020	Non desertification >65% Slight 50-65 Moderate 10-50 High 1-10 Severe <1
	Q. Liu et al., 2020	Non desertification >70% Slight 51-70 Moderate 21-50 High 5-20 Severe <5

The assessment of land degradation and desertification can be done with the same variables and using similar methods, but ultimately with different objectives. This depends on the delimitation given by the author (s). Table 1 show some examples of different thresholds used to assess desertification over changes in vegetation cover. The differences on what is considered bare soil, or arid to when the NDVI reflect the diminution of vegetation, proves that the assessment of degradation or desertification itself, differs from one author to another, giving different results on what is desertification, or when the change becomes irreversible.

To only consider a single variable such as NDVI or vegetation cover change to determine the occurrence of desertification, can lead to an incomplete picture of the desertification phenomena. Therefore, it is better to use multiple variables and establish similar behaviour over time of these variables when studying the desertification phenomenon. Some authors have suggested that monitoring of desertification should be based on the relation between various variables and not on the individual behaviour of a variable, meaning that desertification is in fact the end of a process of degradation (Tereshchenko et al., 2012; Lamchin et al., 2016; Bezerra et al., 2020).

Desertification is now considered an open concept that can be used to refer to related research topics such as land degradation or aridification. This is causing confusion on how to study desertification since the same variables and methods are used to study related concepts. One way to solve this would be to produce thresholds and ranges which determine the presence of risk of desertification. This can help differentiate desertification from similar concepts and can easily be adopted across various countries.

5. Conclusion

Desertification is a topic that is being openly and widely discussed in multiples countries, and at international level. Here we found that studies of desertification using remote sensing data began in 1986 and cover 48 countries, with China being the most studied country. The fact that more than 42% of the articles found in this research are concentrated in one country may skew the global understanding of the process of desertification and its dynamics.

The most used methods to study desertification using remote sensing are change detection and classification, with vegetation and its attributes (e.g., NDVI, land cover, and phenology) being the most used variable. The key purpose of using remote sensing to study desertification was found to be analysis and evaluation of the process of desertification. Surprisingly, few studies have used remote sensing data to predict and simulate future dynamics of desertification. Future studies should focus on this objective as climate change is expected to lead to exacerbation of desertification. Most studies used single variables to study desertification phenomena. However, to only consider a single variable to determine the occurrence of desertification, can lead to an incomplete picture of the desertification phenomena. Therefore, studies that use multiple variables are encouraged.

Currently, most variables and methods used to study desertification are also used to study related concepts such as land degradation. This is leading to a lack of clarity on how to study desertification and its dynamics. Therefore, further research is needed on how to provide an objective measure of desertification and differentiate it from other related concepts such as land degradation. On this line the use of remote sensing data can provide a possible and reachable solution. One approach could be to develop thresholds and ranges of changes of key selected variables, which can be used to determine the presence of desertification.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Asia		Africa		America	
China	177	Morocco	10	Argentina	13
India	18	Egypt	8	Brazil	9
Mongolia	11	Algeria	7	Mexico	6
Iran	9	Burkina Faso	4	United States	5
Iraq	9	Senegal	4	Bolivia	1
Kazakhstan	4	Sudan	2	Chile	1
Saudi Arabia	3	Nigeria	1		
Jordan	2	Benin	1		
Lebanon	2	Eritrea	1		
Russia	2	Ethiopia	1		
Syria	2	Kenya	1		
Tunisia	2	Mauritania	1		
Pakistan	1	Namibia	1		
Israel	1	Zimbabwe	1		
Kyrgyzstan	1	Mozambique	1		
Turkey	1	Libya	1		
		South Africa	1		
Europe				**Regions**	
Spain	6			Sahel	9
Italy	4			Mediterranean	7
Greece	2			World study	7
Portugal	2			Central Asia	5
Romania	2			China-Mongolia-Russia	3
Bosnia and Herzegovina	1			Iberian Peninsula	3
Cyprus	1			sub-Saharan Africa	3
Switzerland	1			Africa	2
Ukraine	1			Asia	2
Oceania				Eastern Asia	2
Australia	1			Europe	2
				Central Asian Newly Independent States	1
				Commonwealth of Independent States (CIS)	1
				Dry Land Asia	1
				South America	1
				Southeast Asia	1
				West Africa	1

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