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Environmental Technology

Applicability of remote sensing technologies in the detection and mapping of prosopis spp species: a systematic review

Aplicabilidade de tecnologias de sensoriamento remoto na detecção e mapeamento de espécies *Prosopis* spp: uma revisão sistemática

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ABSTRACT

Remote sensing plays a crucial role in the detection of invasive alien species. This study aimed to explore and present the existing literature on the use of remote sensing technologies for the detection of invasive *Prosopis* spp canopies in semiarid environments over a long period. A total of fifty studies spanning twelve years were analyzed using the Google Scholar and Science Direct databases, with the help of the ResearchGate social network of researchers and Excel software for data visualization, including word clouds and other graphical representations. The research carried out between 2017 and 2021 witnessed a significant increase in the application of geotechnologies such as Sentinel, LiDAR and hyperspectral images. Vegetation indices, including the Normalized Difference Vegetation Index (NDVI), were widely used. Africa emerged as the continent with the highest level of concern regarding the species discussed, which is evident from the publication of 28 studies. The data revealed that *Prosopis juliflora* showed greater invasive potential in America and Asia. However, African countries, including Kenya, Ethiopia, Somalia and Sudan, faced a high risk of invasion. The terms found most frequently in the analysis were *Prosopis* and *juliflora*. It is essential to prioritize research focused on the application of remote sensing geotechnologies, especially in semiarid regions, to enable informed decision-making by government environmental agencies in relation to the management and control of these invasive species.

Keywords: Geotechnologies; Remote sensing; Invasive species; Mesquite

RESUMO

O sensoriamento remoto é bastante útil na identificação de espécies exóticas invasoras. O objetivo deste estudo foi investigar e relatar, por meio da literatura, o uso de tecnologias de sensoriamento remoto como instrumento na detecção de dosséis invasivos de espécies *Prosopis spp* em ambientes semiáridos ao longo do tempo. Foram utilizados 50 estudos no período espaço-temporal de 12 anos nas bases de dados Google Acadêmico e *Science Direct*, com auxílio da rede social de pesquisadores *Researchgate*, aliado ao uso do Software Excell, para confecção de gráficos, nuvem de palavras e outros arranjos. Foi constatado o aumento das pesquisas entre os anos 2017 e 2021, envolvendo a temática com uso de geotecnologias como o Sentinel, LiDAR e imagens hiperespectrais, Índices de Vegetação, como o Índice de Vegetação da Diferença Normalizada (NDVI), dentre outros. A África apresenta a comunidade mais aflita com as questões referentes às espécies do gênero *Prosopis* contando 28 publicações. Os dados apontam que Prosopis spp., se faz invasiva em maiores proporções na América e na Ásia. Porém, países africanos como Quênia, Etiópia, Somália e Sudão estão sob o alto risco de invasão. Os termos mais frequentes resultantes das análises foram *Prosopis* e *juliflora*. A aplicação de geotecnologias de sensoriamento remoto é imprescindível frente à invasão de Prosopis para tomada de decisões habéis em prol do manejo e controle pelos orgãos ambientais dos governos em regiões semiáridas do mundo.

Palavras-chave: Geotecnologias; Sensoriamento remoto; Espécies invasoras; Algaroba

1 INTRODUCTION

Early detection and mapping of invasive species is crucial for formulating effective management strategies and preventing land invasions (Mbaabu *et al*., 2019). While field survey methods have been used to assess and monitor the plant invasions, remote sensing techniques provide a better estimation and mapping of the invasive species, especially over large spatial extents. Identifying the different invasive species presents a unique challenge as these species' characteristics may be similar to those of native plants. However, the various satellite missions and sensors' ability to acquire data in the spatial, spectral, and temporal resolutions enables detecting and assessing invasive species better (Huang; Asner 2009; Al-Wardy *et al*., 2021). In addition to large-scale analysis, remote sensing has the applicability of monitoring in space.

Among these species, taxa of the genus *Prosopis* (mesquites; Fabaceae) are commonly known as algaroba and are native to Africa, Asia, North America and South America (Aung; Koike, 2015). They comprise a total of 44 known species, distributed in arid and semiarid regions around the world, divided into five sections (Burkart, 1976).

Since then, 13 additional species have been described (Schinini 1981; Earl and Lux 1991; Palacios 2006; Vásquez Núñez *et al*., 2009; De Mera *et al*., 2019; Hughes *et al.*, 2022). Most *Prosopis* species are, however, native to the Americas (López *et al*., 2006).

Remote sensing offers a wider range of sensor systems, such as aerial photographs, multispectral scanners, low- and high-resolution satellite images and ground-based spectrometer measurements (Joshi; Leeuw; Duren, 2003; Amboka; Ngigi, 2015), for monitoring *Prosopis*. As anthropogenic activities evolve, facilitating the spread of *Prosopis* species in arid and semiarid environments, monitoring with sophisticated technologies such as remote sensing becomes indispensable in the face of changes in land use and land cover.

It is clear that there are few published review studies involving the applicability of remote sensing geotechnologies in the detection of invasive *Prosopis* canopies. It is important to note that there are literature review studies focusing on *Prosopis juliflora* pods as fodder resources for livestock (Sawal; Athan; Yadav, 2004), Woody growth of *Prosopis* L. in relation to hydrology in South America (Ambite *et al*., 2022), bioethanol production from algaroba (Sindhu; Gnanavel, 2016), pharmacological potentials of *Prosopis juliflora* (Ukande *et al*., 2019), distribution, impacts and control methods (Abdulahi; Ute; Regasa, 2017), among others. However, there is a scarcity of review studies focusing on the use of remote sensing geotechnologies in the *Prosopis* spp. invasion.

In this context, the guiding question of this research is: What research papers have been published in the last 12 years (2011-2022) on the applicability of remote sensing technologies in relation to the invasion of *Prosopis* species? This review aims to present relevant aspects of the importance of using these technologies and how this topic has been discussed in the literature.

Therefore, the aim of this study was to investigate and report, through the literature, the use of remote sensing technologies as a tool to detect and map invasive *Prosopis* spp canopies in semiarid environments over time.

2 MATERIAL AND METHODS

This study is a systematic investigation (Tranfield; Denyer; Smart, 2003). Predefined systematic methods were employed to identify all relevant published and unpublished documents for the research question, and the quality of these articles was assessed, data extracted and results synthesized (Donato; Donato, 2019). This type of study provides professionals and policymakers with a reliable basis for decision-making and action (Tranfield; Denyer; Smart, 2003).

The literature search and coding were carried out between December 2021 and July 2022, with careful inspection during the first half of 2023. The search was carried out in the following databases: Google Scholar and Science Direct. In addition, the ResearchGate research network was used for data validation. Publications from a 12-year period (2011-2022) were considered.

The period selected (2011-2022) is justified by the fact that the risk of invasion by exotic *Prosopis* spp trees increases with temperature, soil alkalinity and clay fractions (Dakhil *et al*., 2021), as well as with the global increase in biological invasions in recent years. In addition, the invasion of *Prosopis* species is linked to the principles of protection, restoration and sustainable use of ecosystem services, inherent in the 15th Sustainable Development Goal (Un, 2015; Silva *et al*., 2022; Oliveira *et al*., 2020; Choudhary; Ramkumar, 2020).

Therefore, the process of carrying out this study followed the three stages proposed by Tranfield, Denyer and Smart (2003), namely: I. Planning the review; II. Carrying out the research; and III. Reporting and dissemination, as illustrated in the flowchart (Figure 1).

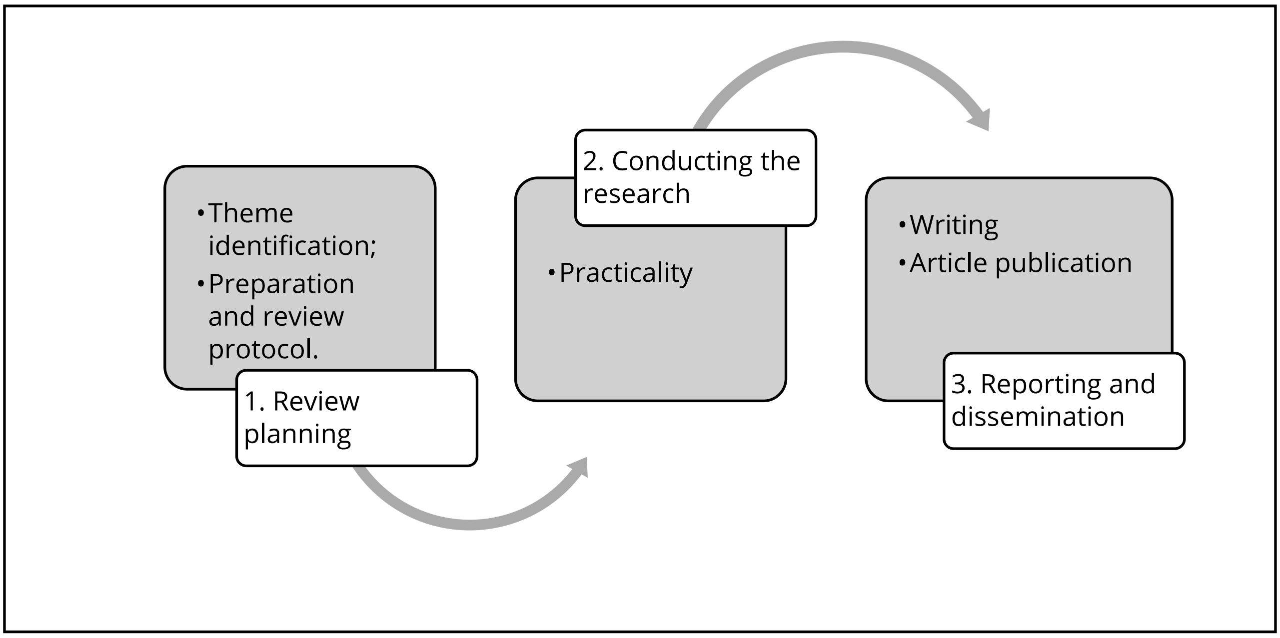
The articles selected included original research, technical reports and review studies focusing on the use of remote sensing to map *Prosopis* species. The articles were selected based on the inclusion or exclusion criteria of their titles and abstracts, and were read in full when the abstracts were not informative. Priority was given to publications that dealt exclusively with remote sensing in the detection of *Prosopis* species.

It is known that recently, based on genomic analyses that studied 997 nuclear genes, the genus *Prosopis* was reorganized and divided into five new genera: *Anonychium, Indopiptadenia, Neltuma, Strombocarpa and Xerocladia* (Hughes *et al.*, 2022). After this split, only three species remained under the original classification of Prosopis (in the strict sense). In addition, the species *Prosopis juliflora* was reclassified and now belongs to the genus *Neltuma*, now called *Neltuma juliflora* (Hughes *et al.*, 2022). In other words, for this systematic review study, we tried to include several species from the genus *Prosopis* spp. before the aforementioned segregation, covering the species that belonged to the genus before being redistributed into other genera, such as *Neltuma* and *Strombocarpa*, e.g.

Quantitative analysis of the sample was carried out using Excel, applying descriptive statistics. After processing the data, it was necessary to construct graphs and tables to present the results (Silva *et al*., 2022; Barreto, 2022). For the qualitative analysis, we used content analysis (Bardin, 2016) and Atlas.ti version 9 software to create word clouds to identify the most frequent terms in the publications. According to Silva Junior and Leão (2018), the software offers several features, including the ability to build state-of-the-art reports, perform multimedia analysis of images, audios and videos, perform statistical data processing, analyze research and code databases.

The frequency of words was determined using the word cloud generated from the textual analysis of a group of texts, corresponding to the titles. Lexical analysis was fundamental to understanding the word cloud (Ramos; Lima; Rosa, 2018; Silva *et al.*, 2022).

Figure 1 – Methodological design used



Source: The authors (2023)

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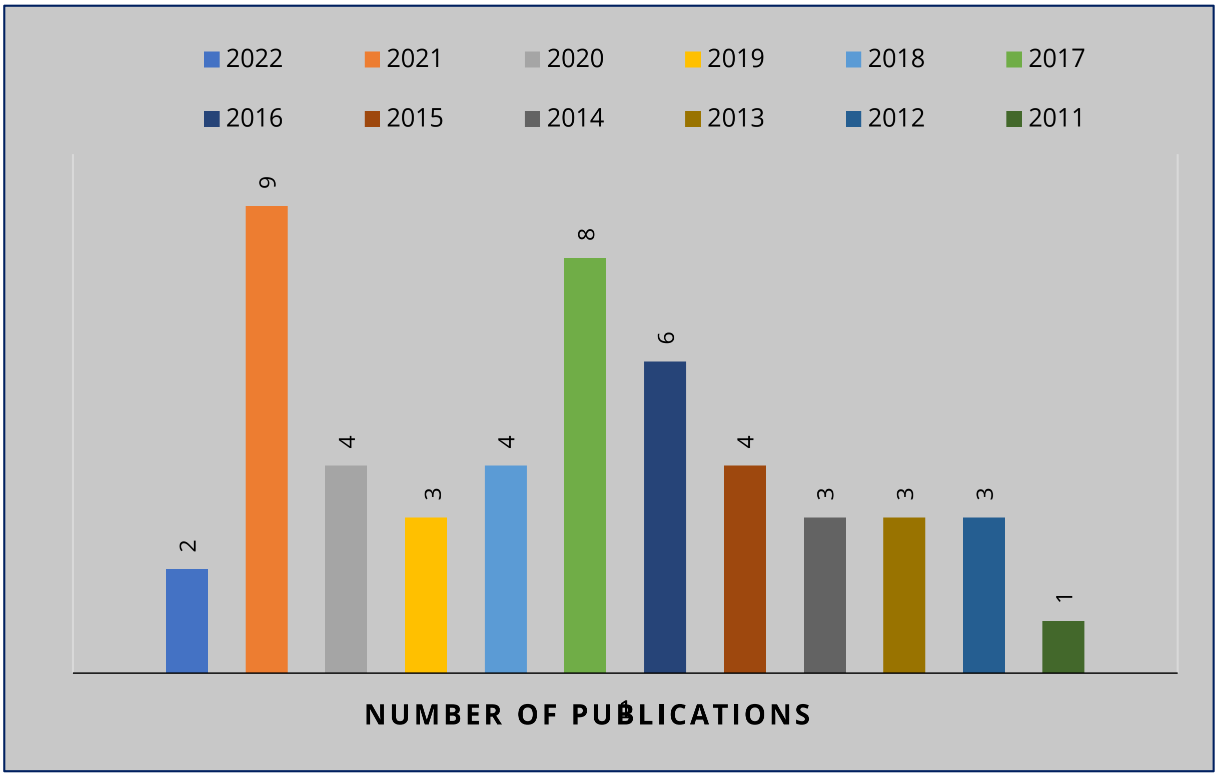
3 RESULTS AND DISCUSSION

3.1 Quantification and classification of publications

The initial search identified 43 publications in Science Direct and 62 publications in Google Scholar, resulting in a total of 105 publications related to the applicability of geotechnologies in the discovery and mapping of invasive species in general. After excluding studies that did not fit the proposed time period or the specific topic of interest, only 50 studies remained.

This research comprised a final sample of 50 articles, a quantitatively significant number considering the spatial and temporal scope of 12 years and, above all, among the countries of the three continents invaded by the species mentioned. Through the analyses carried out during this period, it was observed that the number of scientific publications on the use of remote sensing algorithms in the invasion of *Prosopis* spp species increased significantly over the period studied, indicating a growing interest in this topic from the scientific community (Figure 2).

Figure 2 – Scientific publications on remote sensing applied to invasive species Prosopis spp



Source: The authors (2023)

Likewise, in addition to progress, the current state and future opportunities of remote sensing for the research and management of plant invasions were considered. Since the 1970s, remote sensing has been used (Vaz *et al*., 2018) for trees such as *Prosopis* spp, which have high invasive potential in semiarid environments. Heshmati *et al*. (2019), e.g., using the environmental suitability algorithms species distribution modeling (SDM) and maximum entropy method (MaxEnt), modeled how future climate conditions may influence the advance and retreat of P. *juliflora* areas around the world, and verified stability in areas occupied by this species in northeastern Brazil. This is understandable because, despite the positive impacts provided by *Prosopis*, the species tends to form dense and impenetrable forests with unfavorable consequences (Pasiecznik *et al*., 2001; Adam; Mureriwa; Newete, 2017).

In the Brazilian semiarid region, more specifically in the Riacho do Navio River Basin (BHRN), located in the state of Pernambuco, Carvalho, Lopes and Silva (2019) worked with analysis and classification of historical rainfall series of more than 30 years combined with mapping of land use and occupation using satellite images, the TM/ Landsat 8 sensor with 6R5G4B color composition for supervised classification, found a 4% higher growth for the riparian forest class, caused by the increase in algaroba (*Prosopis juliflora*) (Sw.) DC (Carvalho; Lopes; Silva, 2019), similar to Coelho *et al.* (2014), in a study carried out in the municipality of Serra Talhada, Pernambuco and Santos *et al*. (2019) on the banks of the Apodi-Mossoró River, Rio Grande do Norte State. The *P. juliflora* species currently occupies large areas in all the states of Northeastern Brazil, with estimates of over 500,000 hectares (Lima, 2005; Carneiro-Junior *et al*., 2021).

The above procedure also makes it possible to differentiate Caatinga vegetation from some introduced flora communities, such as *P. juliflora*, which does not lose its leaves during the dry season because it is managed in areas close to bodies of water, such as rivers, which, even if their beds are dry, have an accumulation of groundwater (Silva; Cruz, 2018). In this segment, Cavalcanti (2014), later cited by Souza and Cruz (2018), reveals that this class would be defined as Hygrophilous Formation, and of all the classifications presented, this is the only one in which there is a class for introduced or cosmopolitan vegetation.

These authors also warn that the above example is not sufficient to account for all the complexity of the Caatinga, but is only an approximation of the use of the environmental dynamics inherent in the biome, in support of the classification of orbital remote sensing images (Silva; Cruz, 2018). Northeastern Brazil is subject to phytogeographic changes, which are enhanced by the presence of species that lack effective control or management. *P. juliflora* found a favorable environment for its development in the Caatinga (Nogueira Júnior *et al*., 2019). In this sense, these facts demonstrate how valuable the use of sensing technologies is for the purposes of detecting and mapping *Prosopis* in the Brazilian semiarid, taking into account the risks of future invasions in Caatinga, pasture, irrigated and dryland and degraded areas, respectively.

The concern is alarming, as there was an increase in the number of publications using remote sensing with Prosopis spp trees during the period from 2011 to 2016, especially between 2015 and 2016. Throughout the study period, the number of scientific papers aimed at mapping these highlighted species exceeded expected expectations, indicating a growing formation of scientific groups focused on this subject. In parallel, authors such as Pedreira, Lobão and Vasconcelos (2022), working with scientific productions, through bibliometrics of studies carried out with *P. juliflora*, also found a considerable increase in publications after the 2000s, mainly with a period of greater productivity occurring between 2010 and 2017, with a peak of sixteen productions in 2016.

This increase is noticeable in view of the emergence of various geoprocessing software such as ARQGIS and spectral indices, geospatial data visualizers such as Google Maps TM, EEFLux (Earth Engine Evapotranspiration Flux), LANDSAT satellites, Sentinel, UAVs (Unmanned Aerial Vehicles), and others, some of which are capable of demonstrating better accuracy of the spectral reflectance of the attributes of objects on the ground such as extracts of *Prosopis* tree canopies. According to Huylenbroeck *et al*. (2020), LiDAR seems to be the most commonly used technology to describe vegetation structure characteristics, with the exception of Large Woody Debris, landscape metrics and vegetation cover. However, LiDAR from unmanned aerial vehicles, known as UAVs or Unmanned Aerial Vehicles (UAVs), has proven to be an emerging technology, as it has robust attributes based on scans above and below the canopy (Liang *et al*., 2019; Nishiwaki *et al*., 2023), as did Ku and Popescu (2018) in Texas, USA, comparing three statistical methods and identifying significant predictor variables.

In addition, the use of the high-resolution GeoEye satellite to obtain hyperspectral images, employing two techniques - Derived Vegetation Index and Spectral Angle Mapper in Pakistan (Kazmi *et al*., 2021), vegetation indices such as the Normalized

Difference Vegetation Index (NDVI) in the United Arab Emirates (UAE) (Howari *et al*., 2022) and other techniques have been employed to detect the aforementioned invasive.

Remote sensing plays a crucial role in mapping and monitoring invasive species. Its ability to provide multispectral and multitemporal coverage in a cost-effective manner has made it the number one choice for mapping changes in vegetation cover over a larger geographical area in reasonable timeframes (Stoms; Estes, 1993; Amboka; Ngigi, 2015).

In the first few years (2011 to 2014), the number of publications was limited, with only 10 articles. When evaluating the cumulative number of publications, a pattern is observed between 2018 and 2020, showing a significant increase compared to all other years. However, there is a notable expansion of research during the years 2017 and 2021.

3.2 Spatial classification of survey

It was found that, in the research carried out on the three continents where the tree invades, the five countries with the highest percentage of publications, including Brazil, account for more than 50% of the scientific production on the subject in question. These results are also due to the usefulness and lack of adoption of control methods by each of these countries.

The species *P. juliflora*, e.g. introduced in 1942 in Serra Talhada, Pernambuco, northeast Brazil, is native to the Piura region of Peru (Gomes, 1961; Lima, 1999; Alves et al., 2019). At that time, *P. juliflora* was introduced to feed cattle and reforest deforested areas (Santos; Diodato, 2015), without a thorough knowledge of the species, which ended up intensifying the levels of biological invasion in Caatinga areas, as evidenced by authors such as (Pegado; Andrade; Pereira, 2006; Andrade; Fabricante; Oliveira; 2009, 2010).

Therefore, in Brazil, it is clear that these facts have contributed significantly to the use of remote sensing technologies (Pereira *et al.,* 2013; Santos; Diodato, 2015; Santos *et al.*, 2019; Amador *et al.,* 2011), whose purpose has been the detection, mapping and, subsequently, the management and control of *Prosopis* spp. These and other developments justify the amount of research revealed in this review study.

In terms of continents, Africa has the community most concerned with the issues of invasive species of the genus *Prosopis* spp. due to the various works carried out in these semiarid environments. Despite being considered poor countries with limited scientific knowledge, Ethiopia, e.g., has made significant investments in studies focused on the use of remote sensing to detect *Prosopis* spp, similar to India in Asia. According to Kazmi *et al*. (2022), invasive plant species have dominated urban habitats over the last century, especially in the megacities of South Asia. Most of these species are introduced as a result of planning and design, often for a special purpose (e.g. sand dune stabilization, erosion control, flood control, rapid green roofs, etc.).

This is due to the fact that large areas of semiarid regions in East Africa, e.g., are reportedly invaded by P. juliflora, with rapid expansion, especially in communal grazing areas (Dubow, 2011; Rembold *et al.,* 2015). In addition, agricultural land affected by salts and left fallow is covered by P. juliflora, an exotic evergreen and thorny tree species in India (Bhagat; More, 2013). Consequently, it can be seen that the main research efforts are concentrated in Africa, with a total of 28 publications, mainly carried out in Ethiopia, Kenya and South Africa, respectively.

In order to draw up this scheme, journal articles were mainly taken into account. Priority was given to the countries with the highest number of published articles, namely: Ethiopia, India, Kenya, South Africa and Brazil. These studies partially or totally used remote sensing techniques to detect the *Prosopis* species considered in this research.

Table 1 shows significant variations in the types of satellites used to image the areas of the 25 studies listed. The most widely used satellite based on research evidence was Landsat, due to its high spatial resolution and radiometric accuracy.

Table 1 – Classification of scientific groups by geographic region and type of satellite used

(Continue...)

Title of Publications	**Author and Year**	**Satellite/sensor**
Performance of Species Distribution Modeling and its implication for Sentinel-2-based prediction of invasive *Prosopis juliflora* in the lower Awash River basin, Ethiopia	Ahmed *et al*. (2022)	MODIS
Expansion of *Prosopis juliflora* and land use/land cover change in the Korahey zone of the regional state of Somalia, eastern Ethiopia	Wudad and Abdulahi, (2021)	Landsat
Regional dynamics in the distribution of *Prosopis juliflora* under projected climate change in Africa	Sintayehu *et al*. (2020)	Species Distribution Modeling (SDM)
Effects of *Prosopis juliflora* invasions on land use/land cover change in the South Afar region, Northeast Ethiopia	Shiferaw *et al*. (2019)	Google Earth Pro v. 7.1.5
Assessing the distribution and impacts of *Prosopis juliflora* through participatory approaches	Wakie *et al.* (2016)	Landsat
Spatial mapping of *Prosopis juliflora* (Swartz) DC in Pudukkottai District, Tamil Nadu, India	Hiregoudar *et al*. (2020)	Resourcesat – 2 Linear Imagens Self Scanning LISS (IV)
Mapping of invasive *Prosopis juliflora* in arid regions using high-resolution remote sensing data and biophysical parameters	Vidhya *et al*. (2017)	Landsat
An Autonomous UAV-UGV System for Eradication of the Invasive Weed *Prosopis juliflora*	Baskaran *et al*. (2017)	Landsat, Resourcesat-1/ IRS-P6
Use of LANDSAT ETM+ data for *Prosopis juliflora* detection in irrigated areas	Bhagat and More (2013)	Landsat

Table 1 – Classification of scientific groups by geographic region and type of satellite used

(Continue...)

Title of Publications	Author and Year	Satellite/sensor
Satellite image-based quantification of *Prosopis juliflora* invasion and patch dynamics in the Great Rann of Kachchh, Kachchh Biosphere Reserve, Gujarat, India	Pasha *et al*. (2014)	Resourcesat – 2 Linear, Imagens LISS (IV)
Quantification of *Prosopis juliflora* invasive colonies using remote sensing and GIS techniques	Ragavan and Johnny (2015)	Landsat
Utilizing Geo-information Tools for Mapping Spatio-temporal Changes in Population of *Prosopis cineraria* (khejri) in Agroforestry System of Arid Western Rajasthan	Moharana *et al*. (2018)	Google Earth e satélite IRS-LISS-III
Mapping and Monitoring Spatial-Temporal Land Cover Change of *Prosopis* Species Colonization in Baringo Central, Kenya	Kumar and Mathur (2014)	Landsat
Mapping Prosopis spp. with Landsat 8 data in arid environments: Evaluating effectiveness of different methods and temporal imagery selection for Hargeisa, Somaliland	Ng *et al*. (2016)	Landsat
Assessing the Potential of Sentinel-2 and Pleiades Data for *Prosopi*s and *Vachellia* spp. Detection in Kenya	Ng *et al*. (2017)	Sentinel-2
Machine learning algorithms for mapping Prosopis glandulosa and land cover change using multi-temporal Landsat products: a case study of Prieska in the Northern Cape Province, South Africa	Villiers *et al.* (2020)	Landsat
Mapping *Prosopis glandulosa* (mesquite) in the semi-arid environment of South Africa using high-resolution WorldView-2 imagery and machine learning classifiers	Adam *et al.* (2017)	WorldView-2
Mesquite Risk Mapping and Assessment in Tokar Delta-Eastern Sudan	Suliman *et al*. (2015)	Landsat

Table 1 – Classification of scientific groups by geographic region and type of satellite used

(Conclusion..)

Title of Publications	**Author and Year**	**Satellite/sensor**
Examining the spectral separability of *Prosopis glandulosa* from coexisting species using field spectral measurement and regularized random forest	Mureriwa *et al.* (2016)	Spectroscopy
Spatio-temporal analysis of vegetation cover and *Prosopis juliflora* (SW) DC advancement in a Caatinga area	Pereira *et al.* (2013)	Landsat and CBERS
Distribution and analysis of Prosopis tree dispersion processes in protected urban areas of the municipality of Mossoró/RN	Santos *et al.* (2019)	Shapefile layers with and Google Maps images
Wide-area invasive species propagation mapping is possible using phenometric trends	Landmann *et al*. (2020)	MODIS
Analysis of Prosopis juliflora (SW) invasion in the Caatinga, municipality of Fernando Pedroza, Rio Grande do Norte	Santos and Diodato (2015)	Landsat

Source: The authors (2023)

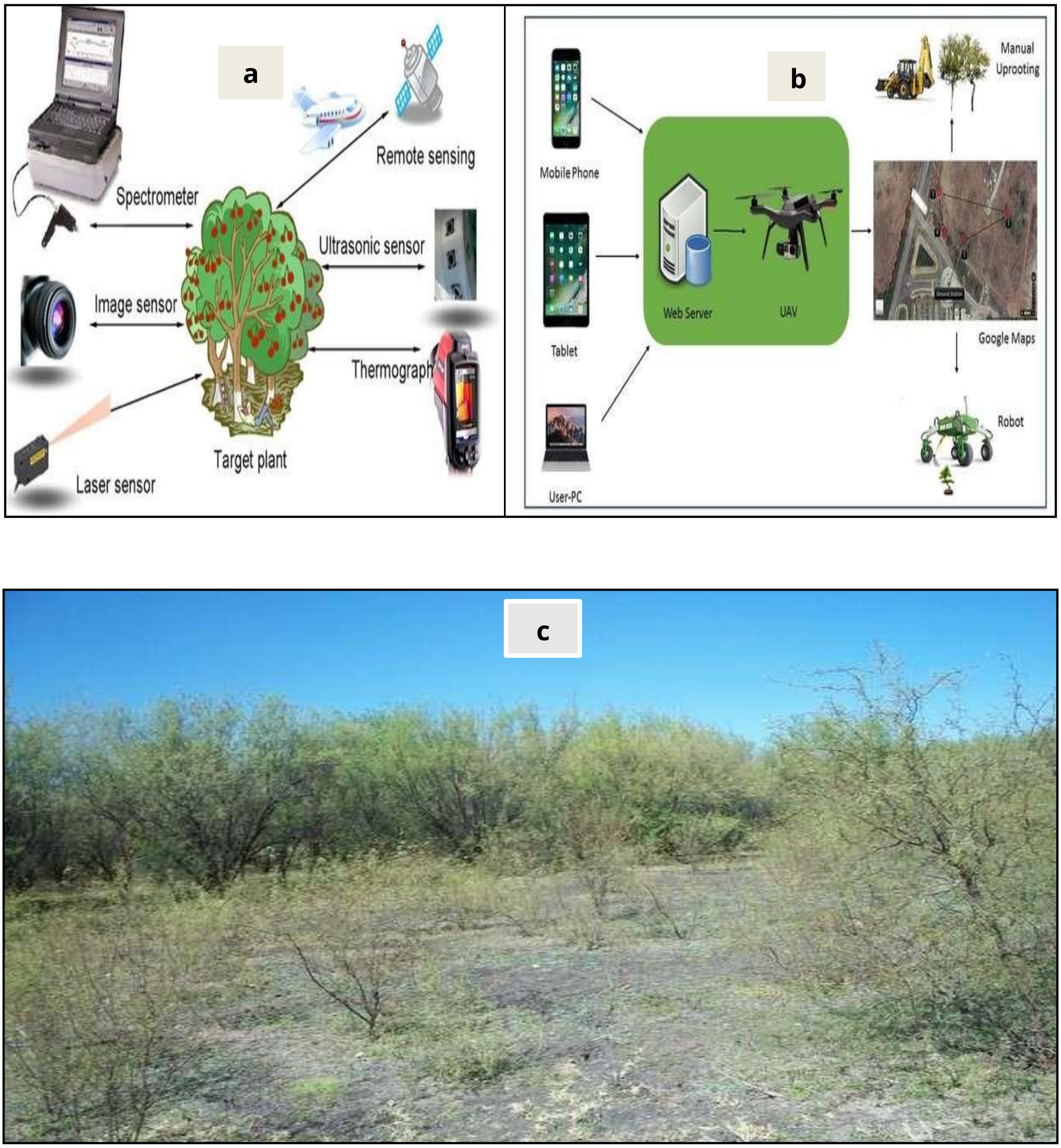
In a study conducted by Al-Wardy *et al*. (2021) in the Salalah Plains, located in the southern part of Oman, using three different satellites: Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and Landsat-8 Operational Land Imager (OLI), the classification accuracy of P. *julifora* was very high (over 90%). Ng et al. (2016) in Hargeisa, Somaliland, were able to classify five different classes of *Prosopis* using Landsat-8/OLI data in wet conditions and dry seasons. Other studies by Meroni *et al.* (2017), Rembold *et al.* (2015) and AlMaazmi and Al-Ruzouq (2021) have also shown the powerful capabilities of Landsat-8/OLI and common classification algorithms in the spatio-temporal identification of *Prosopis* distribution, as well as Pereira *et al.* (2013), who, in the Brazilian semiarid region, attempted to analyze vegetation cover and the expansion of algaroba over a twenty-year period.

The introduction of the Landsat system in 1972 provided a satellite system that covered most of the world. These systems have provided multi-date datasets that allow the monitoring of dynamic landscape features, thus making it possible to detect and quantify any significant change in vegetation cover in space and time. South Africa, India and Sudan are among the countries where remote sensing and GIS technology have been used to map and monitor the colonization of *Prosopis* species. The results showed the potential of remote sensing to detect any form of alien invasion (Lillesand; Kiefer, 1994; Amboka; Ngigi, 2015).

In this sense, it is known that several remote sensing technologies have already been proposed to detect and map invasive *Prosopis* strata. This shows the importance of remote sensing technologies, such as orbital satellites, for detecting and monitoring areas invaded by *Prosopis* species, as shown in (Figure 3).

Figure 3 shows a proposal by Song *et al.* (2015) for an intelligent spraying system by introducing sensing techniques including machine vision, spectral reflectance and remote sensing to help consider a spraying system to address precision agriculture through weed control. Baskaran *et al.* (2017) developed an affordable and innovative aerial vehicle called an unmanned autonomous vehicle (UAV) and an unmanned ground vehicle (UGV) system. The UAV is capable of automatically identifying weed seedlings and sprouts. The UGV is a ground vehicle used to cut down the trees identified by the UAV.

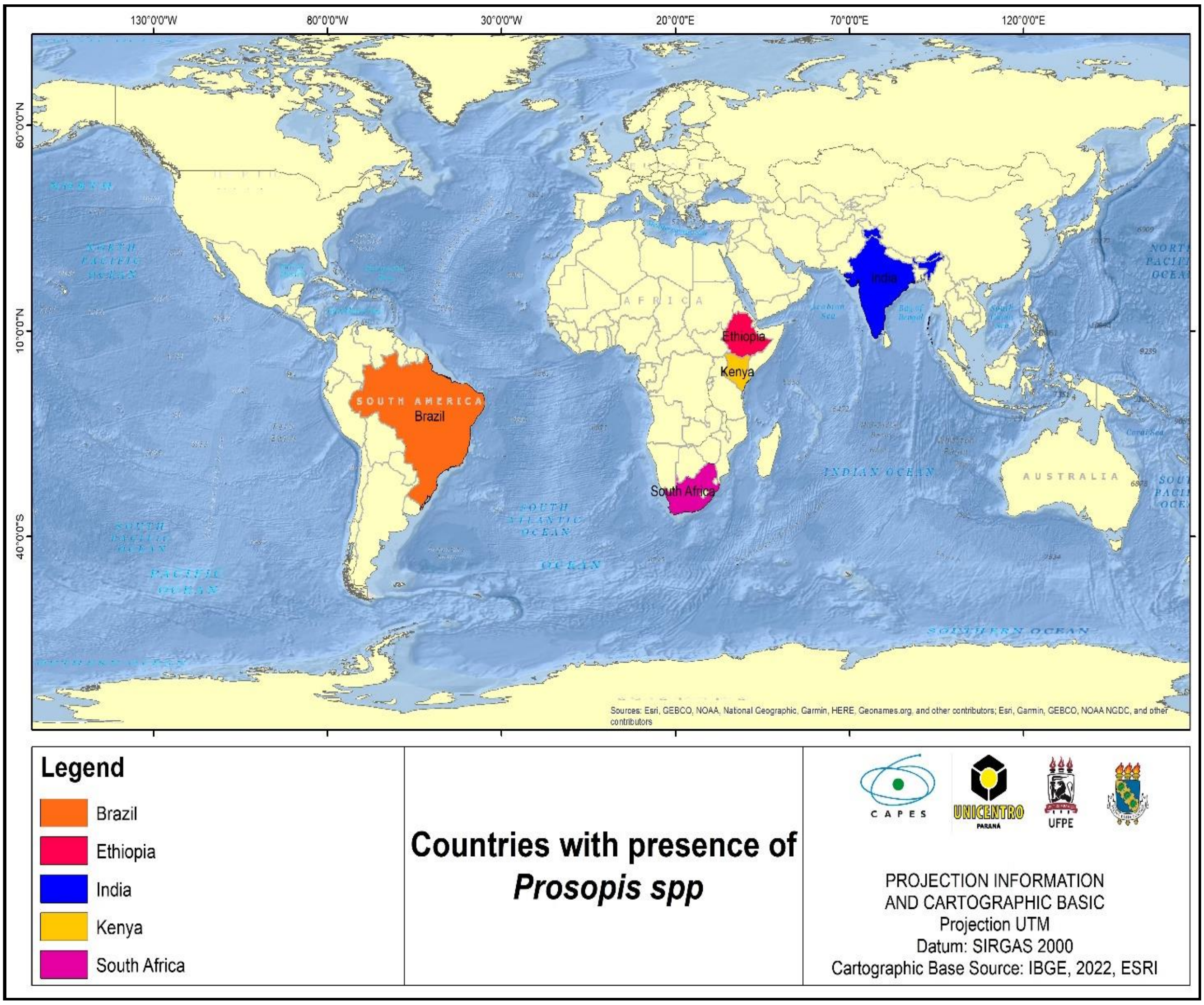
Figure 3 – (a) Targeted Detecting Sensors (Song *et al.*, 2015); (b) Schematic of proposed system by Baskaran *et al.* (2017); (c) *Prosopis velutina* along the riverine system of the Molopo River District in the North-West Province (NWP) of South Africa (Tiawoun *et al.*, 2023). Schemes of how remote sensing can be employed for *Prosopis* species



Source: Song *et al.* (2015); Baskaran *et al.* (2017) and Tiawoun *et al.* (2023)

Interest in employing multispectral remote sensing with high and very high spatial resolution of multitemporal data to study biological invasions in plant communities has grown considerably (Khare *et al*., 2019). Remote detection of invasive alien plants is often difficult, as it occurs in disturbed areas, "mixed pixels" and under the canopy (Bradley, 2014). Multispectral data contains several to hundreds of bands, and hyperspectral data contains hundreds to thousands of contiguous bands. The morphological and spectral characteristics of the image are more important (Song *et al.*, 2015). Thus, (Figure 4) shows some of the countries whose research applied remote sensing to detect *Prosopis* invasion.

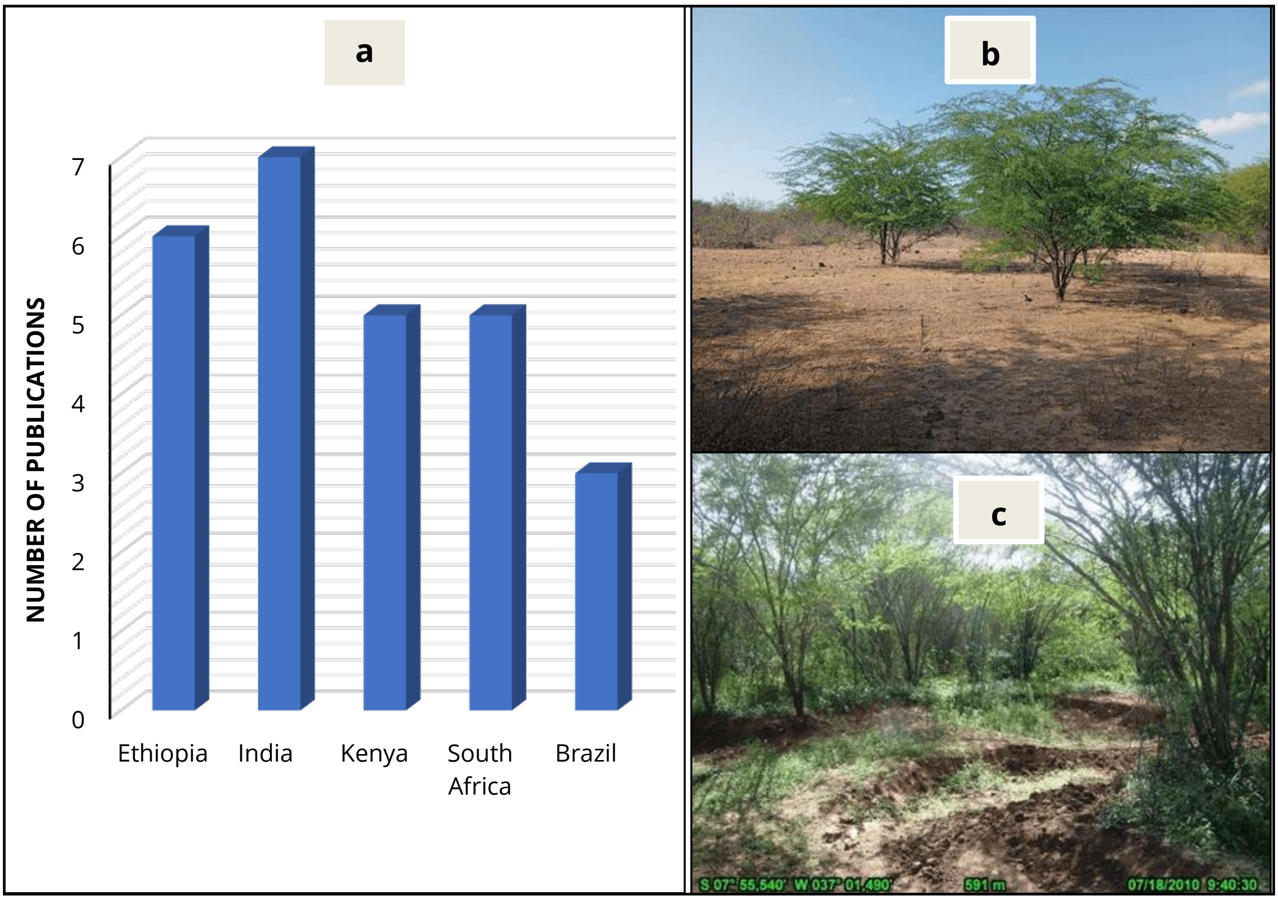
Figure 4 – Countries whose scientific publications on remote sensing were applied to invasive species *Prosopis* spp.



Source: The authors (2022).

Considering Figure 4, which refers to the areas of spread of species of the genus Prosopis spp in the world, based on the research carried out, it is clearer to see which countries have an invasion of these canopies. Tropical and subtropical moist and dry forests (TSMF and TSDF) have a moderate chance of being among the biomes at high risk of invasion. Flooded grasslands and savannas (FGS) and mangroves are less likely to be among the biomes at high risk of invasion (Dakhil *et al.*, 2021) (Figure 5).

Figure 5 – (a) Number of some publications on the topic; (b) *P. juliflora* starting to invade Caatinga area (The authors, 2023); (c) Mesquite trees in the dam area being able to visualize significant soil erosion process, Monteiro, Paraíba, Brazil (Amador *et al*., 2011).



Source: The authors (2023) and Amador *et al*. (2011)

Figure 5 shows India's significant spatial distribution in relation to the number of published studies involving the application of remote sensing for the detection and mapping of *Prosopis* as well as strata of the *P. juliflora* species in the semiarid region of northeastern Brazil.

Müllerová *et al*. (2013) indicate that automated and semi-automated remote sensing approaches are cost-effective solutions for regular monitoring of invasive alien species (IAS). Miao *et al.* (2011) found that hyperspectral aerial imagery with 227 bands and 1-meter resolution can be an alternative for detecting and mapping *Prosopis glandulosa.*

In addition, biophysical variables derived from satellite remote sensing data have a huge contribution to make in describing forest variables (Ahmed; Atzberger; Zewdie, 2021). The lack of up-to-date information on the *Prosopis* invasion has meant that current management and monitoring have been unsuccessful. The identification of *Prosopis* species, their location and rate of spread are key to providing reliable and accurate information on spatial and temporal spread and the level of invasion in the native ecological community (Adam; Mureriwa; Newete, 2017).

According to Choudhary and Ramkumar (2020), remote sensing detection using LANDSAT data and the application of classification algorithms can help monitor and control invasive species. However, it is worth noting that, considering the period studied, several studies have been implemented, including those employing different geotechnologies for the detection of *Prosopis* species in various environments, using different resolutions (Table 2).

As shown in Table 1, invasive stands of *Prosopis* are capable of occupying vast areas in a short period of time and, at the same time, generating positive impacts for communities, such as charcoal production. Therefore, the ability of remote sensors integrated with various satellites to demonstrate the actual presence or absence of the species' invasion becomes relatively simple. In addition, during the analysis, this study also identified the most frequently studied species related to the topic discussed (Table 3).

Table 2 – Comparison of the most relevant studies of areas invaded by *Prosopis*

Author	Location/Study Area	Positive/Negative Impact	Resolution
Walter (2011)	Southern Indian state	Used in coal production, but extensively covered resources.	Needs to eradicate and control further growth.
Hoshino *et al.* (2012)	Sudan, North Africa	Invaded water resources, grazing roads	Proposed remote sensing approach to locate the mesquite.
Haregeweyn *et al.* (2013)	Distant state, Ethiopia	Aggressive invader and expected to cover 30% of total area by 2020.	Management is needed to take significant measures to control growth.
Van den Berg (2013)	Northern Cape city, South Africa	Occupied area increased from 4.13% in 1973 to 28.45% in 2007.	Used remote sensing and geographic image sensing to track *Prosopis* invasions.
Pasha *et al.* (2014)	The Great Rann of Kachchh, Gujarat, India	42.9% of total area invaded by *Prosopis* until 2011. Used for fencing and furniture production.	Need for control measures to be taken by the government to control aggressive growth.
Shackleton (2014)	Global review of *Prosopis*	Worldwide invasive mesquite. Good charcoal producer.	Proposed strategies and plans necessary to control the growth of *Prosopis juliflora.*
Meroni *et al.* (2016)	Somaliland, Ethiopia	9% of the total area has already been occupied.	Random classifier applied to remote sensing data and achieved 84% accuracy in identifying the species.
Vidhya *et al.* (2017)	Ramanathapuram, Tamil Nadu, India	Invasive mesquite.	Applied support vector machine algorithm to classify *Prosopis* coverage.
Baskaran *et al.* (2017)	Tamil Nadu, India	Invasive mesquite.	Proposed UAV-UGV system to track and eradicate Prosopis juliflora.
Mbaabu *et al.* (2019)	Baringo, Kenya	*Prosopis* invading land at a rate of 640 hectares per year	Using random classifier achieved 98.5% accuracy in identifying *Prosopis.*

Source: Choudhary and Ramkumar (2020)

Tabela 3 – Species *Prosopis* identified in this study

Species	Country	Continent
Prosopis glandulosa	United Arab Emirates	Asia
Prosopis cineraria	South Africa, Indian	Africa, Asia
Prosopis juliflora	Saudi Arabia, Brazil	Asia, America, Africa
Prosopis chilensis	Ethiopia	Africa

Source: The authors (2023)

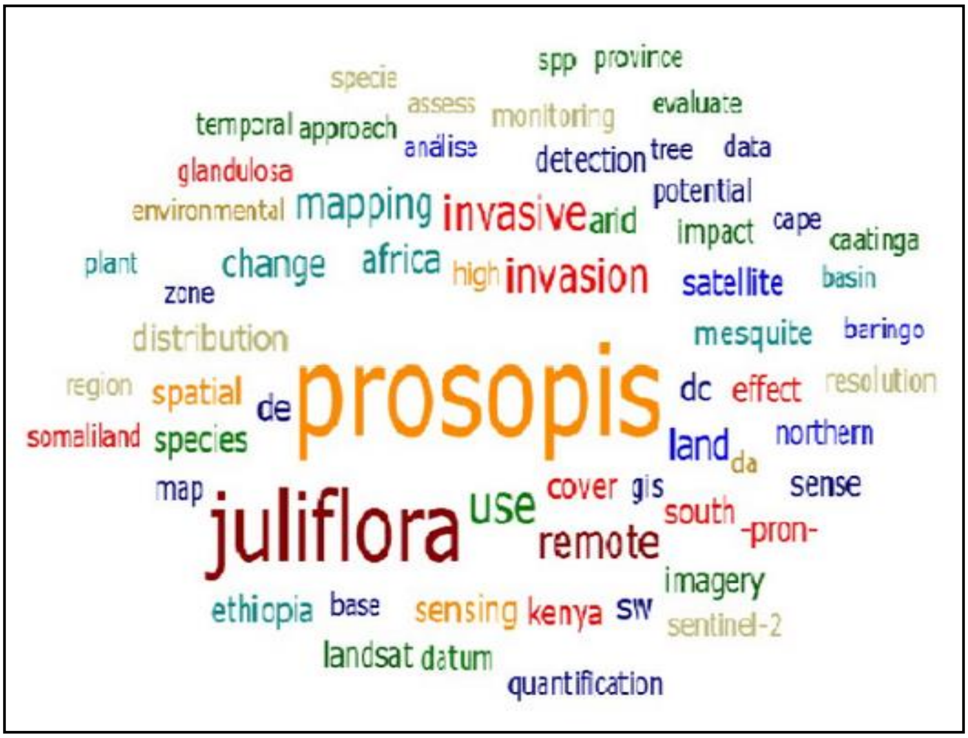
Prosopis juliflora shows proportional invasiveness in environments in the Americas and Asia, while other species, such as *Prosopis* cineraria, tend to have greater adaptability in the arid regions of the African continent, mainly in East Africa. African countries are at high risk of invasion, such as Kenya, Ethiopia, Somalia, South Sudan and Sudan in general, where this species has been introduced for economic purposes, mainly for firewood, timber, fodder and other uses (Mod *et al*., 2016; Wang *et al.*, 2019; Dakhil *et al*., 2021).

3.3 Word Frequency

Word clouds (WC) are graphic representations that show the frequency of words used in a text. Using algorithms, it is possible to build images made up of dozens of words, where the size of each word indicates its frequency or thematic relevance in hundreds or thousands of posts (Vasconcellos-Silva; Araújo-Jorge, 2019).

In this analysis, the words that featured most prominently in the textual review, forming the word cloud, were generated using Atlas.ti software, which allows the study of the words that appear most frequently in the articles analyzed (Sievers; Sprung; Santos, 2017) (Figure 6).

Figure 6 – Cloud Word



Source: The authors (2023)

Figure 6 above shows the 72 words and concepts used most frequently in the titles of research articles. The font size reflects their frequency, with a larger size indicating greater repetition. Words such as *"Prosopis"*, *"juliflora"*, "invasion" and "remote" indicate the rapid colonization of the tree, highlighting the need for measures focused on using remote technologies to identify it.

Terms such as "satellite", "Landsat" and "Datum", commonly used in the field of geotechnologies, geoprocessing and remote sensing, represent the native plants that are negatively affected by *P. juliflora.*

4 CONCLUSIONS

Research focusing on the applicability of remote sensing geotechnologies for the detection or discovery of invasive *Prosopis* spp. trees is still limited, mainly in terms of literature reviews. It is common to address the investigation of the harms and benefits associated with the use of these technologies, as well as to identify the most accurate methods for differentiating the target species from other existing endemic native species.

In Brazil, studies using remote sensing for *Prosopis* species are scarce, despite being one of the ways to monitor the spread of the invasive species in the dry environments of the Brazilian Northeast. It is essential to emphasize the importance of involving other stakeholders in this issue, such as biologists specializing in botany, agronomists and environmental engineers, among others.

Therefore, by forming interdisciplinary teams, it is possible to carry out a more thorough examination and analysis of the invasion strata of the aforementioned tree species, using remote sensing in conjunction with other technologies to identify any damage affecting population groups, especially those residing in rural environments. This collaborative approach will allow government agencies responsible for inspections, environmental monitoring and law enforcement to make informed decisions about the invasion and control of invasive *Prosopis* species.

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