Remote Sensing Applications: Society and Environment 25 (2022) 100689

Contents lists available at ScienceDirect

Remote Sensing Applications: Society and Environment

journal homepage: www.elsevier.com/locate/rsase

# Advancements in the satellite sensing of the impacts of climate and variability on bush encroachment in savannah rangelands

Thabang Maphanga[a,*], Timothy Dube[a], Cletah Shoko[c], Mbulisi Sibanda[b]

[a] Department of Earth Sciences, The University of the Western Cape, Private Bag X17, Bellville, 7535, South Africa
[b] Department of Geography, Environmental Studies, and Tourism, The University of the Western Cape, Private Bag X17, Bellville, 7535, South Africa
[c] Division of Geography, School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Johannesburg, 2050, South Africa

ARTICLE INFO

*Keywords:*
Sub-Saharan Africa
Bush encroachment
Climate change variability
Savannah rangelands
Semi-arid
Remotely-sensed data

ABSTRACT

An increase in shrubs or woody species is likely, directly or indirectly, to significantly affect rural livelihoods, wildlife/livestock productivity and conservation efforts. Poor and inappropriate land use management practices have resulted in rangeland degradation, particularly in semi-arid regions, and this has amplified the bush encroachment rate in many African countries, particularly in key savannah rangelands. The rate of encroachment is also perceived to be connected to other environmental factors, such as climate change, fire and rainfall variability, which may influence the structure and density of the shrubs (woody plants), when compared to uncontrolled grazing. Remote sensing has provided robust data for global studies on both bush encroachment and climate variability over multiple decades, and these data have complemented the local and regional evidence and process studies. This paper thus provides a detailed review of the advancements in the use of remote sensing for the monitoring of bush encroachment on the African continent, which is fuelled by climate variability in the rangeland areas. An understanding of how bush encroachment is fuelled by climate variability and change, as well as its impact on rangelands in the semi-arid areas, is still limited due to the scanty and, at times, fragmented research, especially when it comes to using remote sensing technology. This study also highlights the scientific knowledge gap that exists regarding the impact of climate variability on rangelands, which has yet to be explored by using remotely-sensed data. From a remote sensing viewpoint, rangeland monitoring is challenging when it comes to discriminating between the different herbaceous layers and implementing management practices. Overall, this review emphasizes the increasing role and potential of remote sensing in tracking the impact of climate change on savannah rangelands.

## 1. Introduction

Rangelands are defined as areas that are covered by natural vegetation, predominantly grass, with grass-like plants, forbs and shrubs, which are suitable for wildlife and livestock grazing (Hudak, 1999; James et al., 2003). Bush encroachment poses a serious threat to savannah rangelands globally, but studies have shown that this phenomenon is more prevalent in arid regions (Ward, 2005; Higginbottom et al., 2018; Symeonakis et al., 2016). It is not a new phenomenon, as it has affected savannah rangelands over the past

* Corresponding author.
*E-mail addresses:* Maphangat@cput.ac.za (T. Maphanga), tidube@uwc.ac.za (T. Dube), cletah.shoko@wits.ac.za (C. Shoko), msibanda@uwc.ac.za (M. Sibanda).

https://doi.org/10.1016/j.rsase.2021.100689
Received 31 August 2021; Received in revised form 2 December 2021; Accepted 30 December 2021
Available online 3 January 2022

few decades. Bush encroachment is a complex phenomenon that involves various dynamics, such as changes in the atmospheric $CO_2$ levels, grazing and a variability in the rainfall, which are widespread in Australia, Africa, South America and North America. These rangelands have been linked to climate change and variability, as well as to droughts and land-use patterns, or a combination of the above (Scholes and Archer, 1997; Angassa and Oba, 2008a; Lubetkin et al., 2017). Climate change is responsible for the shift in rainfall patterns, which has severe consequences for the productivity trends on savannah rangelands (See Tables 1 and 2, Fig. 1). Given the threats that are associated with bush encroachment, researchers have started to assess the possible causes (O'Connor et al., 2014), the effects (Palmer and Bennett, 2013; Dube and Pickup, 2001) and the management systems (Liao et al., 2018). Bush encroachment not only reduces the grazing capacity but it also reduces the functioning of the ecosystems, which affects the biodiversity and the annual Gross Domestic Product by 10–17% globally (Ramoelo et al., 2018).

Bush encroachment has a catastrophic impact on the sociology and ecology of a region, more especially when it is combined with climate variability. Climate variability is defined as the varying climatic parameters of a region, which are determined from its long-term mean; these include the erratic and unpredictable seasonal rainfall (Venter et al., 2018). On the African continent, especially in the southern part of the continent, climate change has been associated with a change in the rainfall patterns (Dube and Pickup, 2001; Yang and Crews, 2020). This is more noticeable, as it causes a shift in the vegetation cover, from grasslands to shrubs, which is coupled with overgrazing or different rangeland management practices (Smet and Ward, 2005; Angassa, 2014; Kgosikoma et al., 2012). The variability of rainfall patterns in arid regions has shown that the vegetation in these areas is more sensitive to fluctuations in precipitation, compared to the mesic or xeric and hydric regions (Sankaran et al., 2008; Ponce-Campos et al., 2013). In southern Africa, climate variability and unsustainable grazing patterns have adversely affected the productivity of rangelands (Kgosikoma et al., 2012). A decline in rangeland productivity is associated with bush encroachment, which changes the vegetation density and biomass (Ward, 2005). Therefore, it is pivotal to establish an understanding of how climate variability influences bush encroachment and the different land uses, in order to accurately assess the global ecosystem.

The monitoring of bush encroachment has evolved over the years, from traditional field surveys (Munyati et al., 2009; Belayneh and Tessema, 2017) to the use of remote sensing in the form of aerial photographs (Shantz and Turner, 1958; Madonsela et al., 2017b) and satellite systems (Vogel and Strohbach, 2009; Symeonakis et al., 2016; Baumann et al., 2018). Earth observation technology has produced innovative remote sensors that provide new opportunities and are that considered to be valuable in the context of monitoring the state of the environment (Ludwig et al., 2016; Worku, 2018). For decades, bush encroachment has been increasingly monitored by using remote sensing data, and this technology provides ample advantages, when compared to the use of conventional methods (Dube and Mutanga, 2015; Dougill et al., 2016). Some studies have looked at the status of rangelands (Dube et al., 2019), the mapping of bush encroachment (Oldeland et al., 2010), the ecological impact (Angassa, 2005), bush encroachment monitoring, as well as land degradation and desertification (Symeonakis and Higginbottom, 2014; Graw et al., 2017). The evolution of technologies and strategies for monitoring the threat of bush encroachment has helped to gain a deeper understanding of this phenomenon.

Therefore, effective management is crucial and innovations have been introduced to assist in the improved management of savannah rangelands. This review seeks to provide a detailed overview of the advancements in satellite research that are used to monitor the influence of climate change and variability on bush encroachment in the savannah rangelands. Despite the prevalence and

**Table 1**
The percentages of savannah rangeland that are affected by bush encroachment in some African countries.

| Countries | Rate of encroached area % | Climatic region |
|---|---|---|
| South Africa | 17% | The average annual rainfall for South Africa is about 464 mm. Climate change in South Africa is leading to increased temperatures and rainfall variability. Its varied topography and oceanic influences result in a great variety of climatic zones. Therefore, the rainfall in the east gradually decreases westwards, with some semi-desert areas along the western edge of South Africa (Kakembo and Ndou, 2019). |
| Botswana | 25% | Bush encroachment is prevalent in semi-arid sites where Acacia mellifera Benth. is widespread in communal areas and on private ranches, which shows that land tenure changes over the past 40 years ( Dougill et al., 2016) |
| Tanzania | 12% | The climate varies from tropical, with a relatively high humidity along the coast, to semi-arid on the central plateau, which receives less than 500 mm rainfall per annum. Tanzania is classified as semi-arid, with highly-variable rainfall falling in one or two seasons, which are separated by a long dry season (Borhara et al., 2020) |
| Kenya | 39% | Rainfall is highly variable in space and time, with a generally bimodal pattern. The average annual rainfall ranges from approximately 300 mm in the Amboseli Basin, to over 2000 mm in the highland areas (Kavwele et al., 2017). |
| Zambia | 26% | Rainfall varies over a range of 500 to 1400 mm. The climate in Zambia is tropical or sub-tropical, depending on the altitude (Graw et al., 2016) |
| Namibia | 32% | The encroached areas in Namibia fall mainly into the semi-arid savannahs, with rainfall varying from about 300 mm in the west, to about 500 mm in the north-eastern parts. Southern Namibia exhibits a mix of small shrubs, as well as annual and perennial grasses (Archer et al., 2011). |
| Ethiopia (the Borana Zone in southern Ethiopia) | 19% | The country is dominated by a semi-arid climate. Its mean annual rainfall distribution is a maximum of >2000 mm over the south-western highlands and a minimum of <300 mm over the south-eastern and north-eastern lowlands. The rainfall also varies and increases with the rising altitude. It is estimated that there has been an increase in precipitation variability, with a rising frequency of extreme flooding and droughts, due to global warming (Angassa and Oba, 2007). |

**Table 2**
The table below summarizes the key results demonstrating the role of remote sensing in climate change and bush encroachment.

| Resolutions | | | | | | |
|---|---|---|---|---|---|---|
| Satellite Sensor | Spatial | Temporal | Spectral | Study | Accuracies attained | Author |
| Moderate Resolution Imaging Spectroradiometer (MODIS) | 250 m to 1 km | 2 days | 36 bands | The study used remote sensing models to predict the density, cover and biomass of the three main vegetation forms in savanna ecosystems, namely, trees, shrubs and grasses, in the Etosha National Park, Namibia, using MODIS. | 82% | Tsalyuk et al. (2017) |
| National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR) | 1–4 km | Daily | 5 bands | The study showed that seasonal dynamics of rainfall variation had an impact on the ecological growth of bush cover in the Kalahari of Botswana. | 75% | Dougill and Trodd (1999) |
| IKONOS | 0.82–4 m | 3 days | 5 bands | The study investigated the effects of shrub encroachment on the abundance and diversity of ground-dwelling (wingless) arthropods at varying levels of shrub cover in the southern Kalahari. the ground-dwelling arthropods showed clear shifts in species assemblage composition at a similarity level of 65%, according to the shrub density. | 78% | Wasiolka and Blaum (2011) |
| Sentinel 2 MSI | 10–60 m | 5 days | 10 bands | The study showed the potential of satellite- and machine-learning-based approaches in the large-scale mapping of woody vegetation and ongoing bush encroachment in the Molopo area, South Africa. The resulting model and map of woody vegetation cover for this region can be regarded as a basis for further a pattern analysis of bush encroachment. | 90% | Ludwig et al. (2019) |
| SPOT 5 | 2.5–20 m | 2–3 days | 4 bands (Band 1, 0.50–0.59 μm; Band 2, 0.61–0.68 μm; Band 3, 0.78–0.89 μm; Band 4, 1.58–1.75 μm) | The study utilized multi-temporal SPOT images of two rangeland sites in Mokopane, South Africa, for monitoring and assessing bush encroachment in two different rangeland management systems | 89% | Munyati et al. (2011) |
| SPOT-6 | 1.5–6 m | Daily | 4 bands 0.4–0.7 μm | The study looked at the change in woody cover in the Kruger National Park, compared to other factors like rainfall. It was found that low rainfall alone is unlikely to cause a reduction in the woody cover, which suggests that it has adapted to drought. | 93.8% | Munyati and Sinthumule (2016) |
| Landsat 5 TM | 30–120 m | 16 days | 7 bands | The study used multi-seasonal to map fractional woody cover in semi-arid savannah in the east, the Kruger National Park, Limpopo South Africa | 77% | Higginbottom et al. (2018) |
| Landsat 7 ETM+ | 15–60 m | 16 days | 8 bands | The study utilized multi-temporal Landsat 7 ETM+ (SLC-on) data from 1989 until 2009 for monitoring the bush encroachment-related land degradation in a savannah environment in the North-West Province of South Africa, which is mostly from the dry season, and from ancillary data in a GIS environment. The main focus was on mapping bush encroachment. | 89% | Symeonakis and Higginbottom (2014) |
| Landsat 8 OLI | 15–100 m | 16 days | 11 bands | The use of a multispectral bands highlighted the role of precipitation and intraspecific competition in | 87% | Yang and Crews (2020) |

(continued on next page)

**Table 2** (*continued*)

| Resolutions | | | | | | |
|---|---|---|---|---|---|---|
| Satellite Sensor | Spatial | Temporal | Spectral | Study | Accuracies attained | Author |
| | | | | juniper encroachment: Texas savanna. The study noted that the encroachment rate increases as the woody cover deficit increases to about 62%, and then it decreases, with the further increase in the woody cover deficit. | | |
| WorldView-2 | 0.46–2.4 m | 1–3 days | 8 bands | The study was conducted in the Kruger National Park, where WorldView-2 spectral configuration was used to help discriminate between the tree species in a southern African savannah environment | 96.5% | Madonsela et al. (2017) |
| QuickBird | 65 cm to 2.90 m | 1–3 days | 5 bands | A study conducted in southern New Mexico researched the vegetation dynamics that reflected changes in precipitation patterns; in particular, the effects of the 1951–1956 drought. The research assessed the rate of shrub encroachment into a desert grassland by using remotely sensed imagery. It was found that the shrub cover increased and grass cover decreased over time, but these changes were non-linear | 87% | Laliberte et al. (2004) |

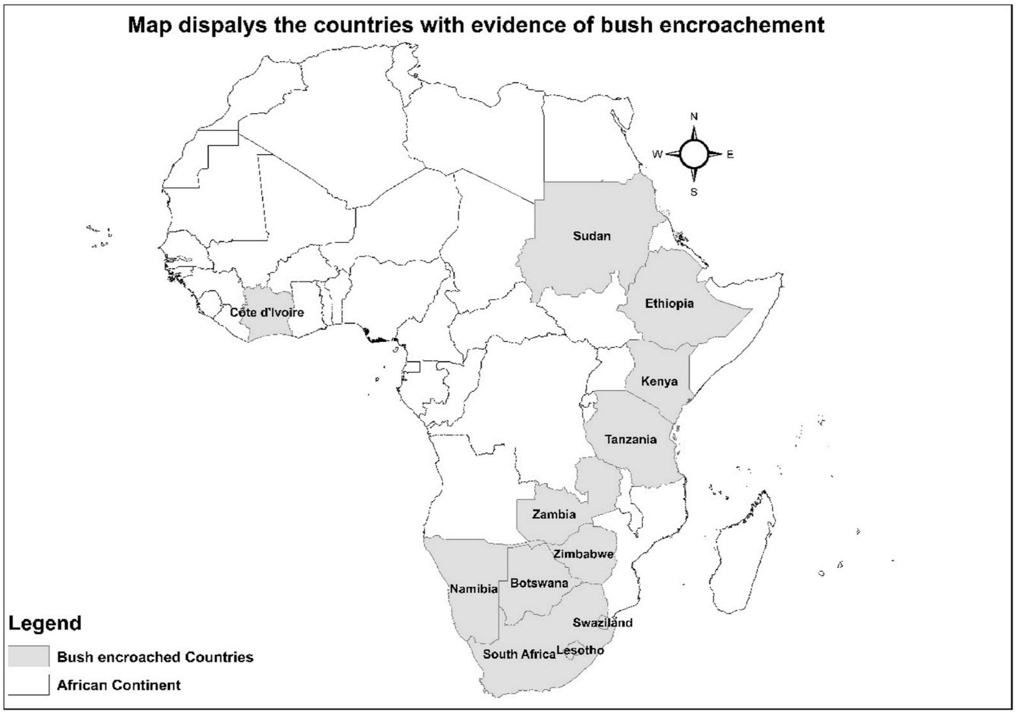


**Fig. 1.** The map displaying the countries that are addressed in this review i.e. the countries in which bush encroachment features.

magnitude of bush encroachment on the different land uses, in both protected and unprotected areas, to the best of our knowledge, limited research has been conducted on documenting the progress in remote sensing applications.

## 2. Literature review methods

The literature search included English peer-reviewed articles and relevant reports. All information used in the evaluation and review was collected from extensive project reports, published papers and websites. The Google Scholar database and Web of Science were used to identify all the relevant articles and reports. The criteria for selection included the following: (1) the assessment of bush encroachment in rangelands (savannah) using remote sensing; (2) the use of remote sensing for monitoring the influence of climate variability on bush encroachment; (3) the impact of climate variability and change on bush encroachment in savannah areas; (4) the effect of bush encroachment on different land uses (commercial and communal); (5) the application of remote sensing in the assessment and monitoring of bush encroachment and climate variation and change; and (6) the link between climate variability and bush encroachment, just to mention few. However, the literature search focused on shrubs (woody plants), tree and bush encroachment, climate change and climate variability in both protected and unprotected areas. Each article was assessed according to the accuracy of its results, and the systematic review and meta-analyses used for the selection of articles are included in our discussion.

## 3. The role and significance of savannah rangelands in Africa

It is estimated that approximately 30% of the global land surface is covered by savannah rangelands, which are mainly characterised by high climate variability and a sensitivity to land use management. Over 250 million households across the globe depend directly on savannah rangelands for their livelihoods. Therefore, the health of these rangelands is critical, due to the ecosystem services that are derived from them. The estimation of Africa's rangeland area varies, depending on the literature source, but it ranges from 22.7% to 41% (FAO, 2013; D'Adamo et al., 2021). Savannah rangelands support approximately 21% of the population in Africa, which depends directly on their ecosystems services or resources. These rangelands are one of the biomes that have great ecological significance, because they provide vital services, such as the sequestration of large amounts of carbon into the soil (Venter et al., 2018), thereby avoiding carbon losses into the atmosphere, which is usually observed when rangelands are transformed to cropland (Sala and Paruelo, 1997). It is estimated that savannah rangelands store more than 30% of the world's soil carbon; this is in addition to the considerable amount of above-ground carbon stored in the trees, shrubs and grasses in their natural state, when is grazed moderately (Angassa, 2005; Bikila et al., 2016). Given the nature of bush encroachment in arid savannah rangelands, higher levels of soil carbon sequestration may be observed during the early stages of encroachment, but they may decline due to the increased encroachment (Hudak and Brockett, 2004; Bikila et al., 2016). Savannah rangelands are potentially beneficial for the global carbon budget, and their effects on communal areas (rural livelihoods) have encouraged many governments to invest in the clearing of alien and native invasive woody plants (Venter et al., 2018).

The health of rangelands is important as it affects the ecological well-being of the plants and animals that depend on it. Approximately 89% of the rural communities depend on the ecosystem services offered by rangelands (Thondhlana and Muchapondwa, 2014). They also contribute to the Gross Domestic Product (GDP), and it was estimated that the economies of African countries grew by 3.2% in 2013 (Muchapondwa and Stage, 2013). For example, wildlife productivity in the rangelands of South Africa is linked to the amount of forage, which is translated to economic growth through tourism and which accounted for an employment rate of around 9% in 2019 (Department of Environment Affairs and Tourism, 1997; Dube et al., 2019). Meanwhile, Arntzen (1998) noted that degraded rangelands had an economic loss of approximately US$ 7 per hectare in the communal areas of Botswana. Traditionally, the economic value estimates of rangelands are based on the production of forage, firewood, medicinal plants and wild fruits, just to mention a few (Abate and Angassa, 2016; Angassa, 2005; Angassa and Oba, 2007). These parameters are taken into consideration as part of rangeland-based economies. Therefore, rangeland management, assessment and restoration would benefit from the advancement of fast, efficient and synoptic quantitative techniques, in concert with indigenous knowledge systems. In Namibia, the estimated value of ecosystem services from the restoration of bush encroachment was US$5.8 billion (Stafford et al., 2017). Despite its significance, it still faces the challenge of degradation and the overutilization of resources, such as the loss of forage and biodiversity, therefore the profound management of rangelands is crucial, and innovations have been introduced to assist and improve their management.

## 4. Occurrence and impacts of climate variability on bush encroachment

Ecosystems rangelands have been adversely affected by climate change and anthropogenic activities, which have disrupted their ecosystem services and spatial configuration, especially in the arid savannah rangelands in Africa (Stafford et al., 2017). Literature has shown that anthropogenic activities also influence bush encroachment and some of these activities are interlinked. These anthropogenic activities include the suppression of fires, overgrazing, cultivation, population pressure and climate change (O'Connor et al., 2014). More often than not, one of these activities can trigger a series of events that contributes to the further degradation of rangelands; for example, desertification can be a result of overgrazing. This eventually leads to the deterioration of soil fertility, soil erosion and the depletion of biodiversity (Kraaij and Ward, 2006; O'Connor et al., 2014; Madonsela et al., 2017).

Climate change has a major influence in the shifting of rangelands from dominated grass species to more woody species (Angassa et al., 2010; Dean and Macdonald, 1994). This is because they are generally found in arid regions and the subsequent bush encroachment is linked with the inter-annual rainfall (Angassa and Oba, 2007). However, there is no clear awareness on how natural factors, such as volcanic eruptions and natural changes in the Greenhouse Gas (GHG) concentrations contribute to the effects of climate change on savannah rangelands. Scientists like Scholtz et al. (2018) stated that other natural factors do not contribute to the effects of climate change on rangelands and that factors, such as soil texture, have no significant effect on bush encroachment in the south-central Great Plains of the US. This is contrary to the findings of Ji et al. (2019), who found that a high clay content (>18%) can reduce the water availability for woody plants or shrubs in south-western US. They also noted that increasing anthropogenic $CO_2$ in the atmosphere had implications for the fertility of the study area in south-western US., thereby fuelling the phenomenon of bush encroachment.

According to the literature, climate variability in arid regions increases the competition for the limited water, especially in areas with a high shrub density, resulting in the death of other plants, particularly during the drought seasons, thus reducing bush encroachment (Ludwig et al., 2019; Madonsela et al., 2017). Some scholars noted that, high precipitation, on a local scale, in the same arid environment over multiple years, promotes an increase in the bush encroachment cover, which requires at least three years of successive good rainfall to establish successfully (Joubert et al., 2008; Belayneh and Tessema, 2017). Bush encroachment is a complicated natural phenomenon that is influenced by moribund and the recruitment of woody plant species, in response to the rainfall patterns (Baumann et al., 2018; Belayneh and Tessema, 2017). Several studies have shown the linkage between bush encroachment and droughts, which is mostly exacerbated by the lack of precipitation, more especially in arid regions (Yang and Crews, 2020; Ludwig et al., 2016). Yang and Crews (2020) stated that the phenomenon of bush encroachment increases with the deficit of woody cover in arid regions because the woody cover deficit can be a proxy for the availability of water for woody plants. Although this might be true in sub-Saharan Africa, particularly in the southern parts, bush encroachment is positively and linearly correlated with water availability, but in other regions, like the arid regions of Australia, it could be the opposite (Axelsson and Hanan, 2017; Borhara et al., 2020; Chen et al., 2016). The effects are observed in a change in the carrying-capacity and complexity of the vegetation. Other global change pressures, including rising temperatures and the increased occurrence of extreme events, such as droughts and erratic rainfall patterns, are also impacting the functioning of rangeland systems (Palmer and Bennett, 2013; Ramoelo et al., 2018).

Climate variability and change has a major influence on the shifting of rangelands from being dominated grass species to being dominated by more woody species (Symeonakis et al., 2016). It all depends on the weather patterns of a particular environment. In addition, bush encroachment affects the soil moisture and competition for nutrients among the shrubs or woody vegetation in arid savannah rangelands. The literature has shown that the variation in vegetation cover in the African savannah rangelands increases when the annual precipitation is between 200 and 700 mm (Sankaran et al., 2008; Higginbottom et al., 2018; Axelsson and Hanan, 2017). Climate variability has increased the frequency of droughts, compared to the unreliable intensity of rainfall, and it drives the rangeland conditions and impacts the availability of fodder for both the livestock and wildlife. It is estimated that bush encroachment in East Africa has increased by 10%, which therefore reduces the grazing capacity by 7% and the grazing areas are eliminated by 90% bush cover (Kakembo and Ndou, 2019; Angassa, 2005). Precipitation is the most important climate parameter that influences the productivity and processes of arid savannah rangelands. The effects of climate change are responsible for the shift in rainfall patterns, which has severe consequences for the dynamics of savannah rangelands (Sankaran et al., 2008; Ponce-Campos et al., 2013). Research has demonstrated that rainfall variability in the arid savannah areas was the primary determining factor for the vegetation dynamics of rangelands, when assessing the rate of bush encroachment, particularly in communal areas (Kraaij and Ward 2006; Dube and Pickup, 2001). The increase in rainfall and the proper management of rangelands, in both protected and communal areas, tend to mitigate the encroachment, while a low precipitation increases the high occurrence of bush encroachment drivers (Venter et al., 2018). In Africa, bush encroachment is an ever-increasing threat as it affects the productivity of rangelands, which also affects the rural livelihoods. Climate change has a major influence on the shift from dominated grass species to more woody species in rangelands (Piao et al., 2014). It all depends on the weather patterns of a particular environment. As a result of climate change, droughts cause devastating problems for rangelands and livestock production systems in Africa. It is important to note that the phenomenon of bush encroachment has been exacerbated by the effects of climate change, which are associated with warming and wet climates, but regional changes in the number of fires, grazing and anthropogenic disturbance, like deforestation, predominate (Venter et al., 2018).

A high annual rainfall variability rate in the semi-arid African savannahs is represented by a high variation in vegetation cover when there is no external disturbance. Hence, the process of bush encroachment, with respect to grazing pressure (in protected and unprotected areas) and the rate of precipitation correlate with each other (Angassa and Oba, 2010; Paudel and Andersen, 2010). Due to the variability of rainfall in arid and semi-arid savannahs, grazing pressure has the potential to exacerbate bush encroachment (Parente et al., 2019; Bunting et al., 2019). The effects of climate change and variability can exacerbate bush encroachment, but the it is difficult to differente between the anthropogenic and climatic drivers of vegetation cover degradation (Lubetkin et al., 2017). The decline in biomass (herbaceous) is linked to both the grazing pressure and precipitation variability.

The impact of bush encroachment varies with the rangeland management practices, as well as other factors, such as the precipitation, the grazing pressure and the environmental gradient (altitude). Some studies have been conducted on the role of an environmental gradient on the variations in precipitation and on the bush encroachment of savannah rangeland (Sankaran et al., 2008; Yang and Crews, 2020), while other studies have demonstrated a varying pattern of woody vegetation across different rainfall levels in the African savannah rangelands (Axelsson and Hanan 2017). However, it is important to note that the process of bush encroachment is a non-linear ecological process. The variations in climatic conditions also have the potential to override the effect of anthropogenic degradation, so that the herbaceous layer can be restored or be further degraded during extreme precipitation, regardless of the grazing pressure (Higginbottom et al., 2018; Symeonakis et al., 2016).

Bush encroachment is an ever-increasing threat in Africa as it affects the productivity of rangeland, which also affects rural livelihoods, either directly or indirectly. Drought is a common threat that affects the southern African savannah rangelands, as this region is mostly semi-arid. Countries like South Africa, Zambia, Botswana, Namibia and Zimbabwe have observed the effects of climate variability and change, which has disrupted the grazing land, and therefore reduced the biodiversity (Dube and Nhamo, 2020). This is equally valid within the context of the National Parks, where the abovementioned countries have seen the disruption of the wildlife migration patterns (Naidoo et al., 2012; Dube and Nhamo, 2020). Prolonged drought conditions can modify the response of vegetation growth to temperature change (Ramoelo et al., 2018), and some species can also gradually adjust to continuous warming by the acclimatisation of their physiological responses, which normally happens in the favour of woody plants (Liao et al., 2018).

The environmental gradient also modulates the role of the variations in precipitation on the encroachment of savannah rangelands. Therefore, prolonged drought conditions may cause the contraction of shrub clusters and the expansion of grass (herbaceous) layers, while above-average precipitation may result in enhanced shrub vegetation (Sankaran et al., 2008; Angassa and Oba, 2007; Yang and Crews, 2020). Throughout literature, it has been demonstrated that almost all the other African countries have experienced net encroachment, except for the Congo, Madagascar, Niger and Somalia, which have experienced a net decline in woody cover (Baumann et al., 2018; Symeonakis and Higginbottom, 2014; Belayneh and Tessema, 2017). The influence of climate (precipitation) is important for the composition of vegetation cover, but from the southern African perspective, the literature suggests that, historically, there is higher grazing pressure in dryland rangelands than any underlying changes in the rainfall (Higginbottom et al., 2018; Muchapondwa and Stage, 2013; Wasiolka and Blaum, 2011).

Climate variability in southern Africa is associated mainly with low and erratic precipitation, which leads to droughts. It is pivotal to understand how rangelands respond to climate variability, in order to accurately assess the global ecosystem system. In the South African context, the phenomenon of bush encroachment has presented serious socio-economic concerns, where other forms of agriculture are not feasible, on account of the low rainfall. This is evident in the communal rangelands of South Africa where people and livestock population densities are very high and where there is heavy grazing, which often leads to bush encroachment (Kraaij and Ward, 2006). There is a long history of communal grazing within many of these areas, as well as the associated claims of land degradation. According to Symeonakis et al. (2016), bush encroachment has reduced the carrying-capacity for grazing to 50%, leaving 1.1 million ha of South African savannah rangelands unusable. Symeonakis et al. (2016) stated further that approximately 27 million ha (17%) of the savannah rangeland in South Africa is still under threat by bush encroachment. Rangeland degradation in South Africa is a serious discussion that has polarized protected (commercial) and communal areas. The table shows the most bush-encroached African countries and the climatic zones, where encroachment is dominant.

## 5. Monitoring climate change and its variable effects on bush encroachment in savannah rangelands

Two main techniques are used for monitoring and assessing the encroachment, condition and quality of rangelands, namely, traditional field data collection and remote sensing. Rangeland monitoring has a strong tradition in many African countries, especially in the southern part of the continent (O'Connor et al., 2014). A significant number of monitoring efforts were established in the 1970s and 1980s, and some even before that (O'Connor et al., 2007). However, some have become defunct over the past ten years. The first formal rangeland condition assessment was developed in South Africa by Foran et al. (1978) and was based on the approach established by Dyksterhuis (1949). This is in contrast with the developed nations, which have enjoyed the use of remotely-sensed data to assess and monitor bush encroachment since the early 20th century, while developing nations, like South Africa, are still using the manual methods (O'Connor et al., 2014). It is important to note that the process of monitoring bush encroachment is a non-linear ecological process; for example, prolonged drought conditions may cause the contraction of shrub clusters and the expansion of grass (herbaceous) layers, while above-average precipitation may result in enhanced shrub vegetation. The increase in precipitation has been shown to correlate with bush encroachment, whereas the influence of the temperature trends is not yet clear (Baumann et al., 2018). The variation in climatic conditions has the potential to override the effects of anthropogenic degradation (e.g. overgrazing) so that the herbaceous layer can be restored or be further degraded during extreme precipitation, regardless of the grazing pressure (Higginbottom et al., 2018; Symeonakis et al., 2016). There is a mounting debate regarding the role of global climate change in bush encroachment, especially with regard to increases in the variability of precipitation.

### *5.1. Bush encroachment monitoring and assessment using traditional methods*

The monitoring of bush encroachment is a vital task, as it allows farmers and rangeland managers to identify these areas, for management purposes (Ludwig et al., 2016; Keno and Suryabhagavan, 2014). The simplest traditional monitoring approach requires a minimum of more than one site as a representative of the area being established in each ecosystem or grassland of management practice. This has enabled the land users and/or managers to detect the changes in the performance level, which can be evident only through the annual monitoring of rangeland sites (Thondhlana and Muchapondwa, 2014). Several models have been deployed to monitor bush encroachment coverage, but some of them still make use of the traditional survey system to assess encroachment on a local scale; these include the contact-based methods (Godinez-Alvare et al., 2009). These methods range from the use of photo traps to contact-based monitoring; for example: 1) the in-field assessment of bush densities in the savannah rangelands is another way of assessing bush encroachment; 2) Competition-based models emphasise competitive interactions in determining the co-existence of trees and grass, with their co-existence resulting from spatial or temporal niche separation; 3) Fixed-point photographs provide a visual impression of the changes in particular sites. For more methods that were, or are being, used to monitor bush encroachment coverage in savannah rangeland, see Trollope (1980). The traditional field-based methods for the collection of information about the condition of the soils, vegetation and water on savannah rangelands, necessitate continuous assessment. These continuous assessments focuses on the biomass quality, the function of fire, nutrition and bush encroachment (Mudongo et al., 2016).

The above methods (1, 2 and 3) allow for the incorporation of the composition of the vegetation, which has been widely used to formally characterize the biological location and to assess the status of rangelands, in terms of the quantitative proportions of species and plant types by weight, density or cover. The traditional methods of monitoring rangelands (Methods 1 and 2) provide the vegetation composition, in terms of the amounts or proportions of native versus non-native grasses, perennial versus annual grasses, the perceived nutritional value and palatability of different species, as well as the plant vigour and growth stage, which are all factors that are required for informal forage quantity estimates. The infield assessment of bush densities in the savannah rangelands is another way of assessing bush encroachment, which looks at the encroached area in relation to the carrying-capacity of the rangeland. Integrating these methods becomes difficult without using remotely-sensed monitored data. Traditional Methods 1 and 2 make use of the line intercept method to estimate the tree and shrub cover by measuring the intersect distance along each belt to produce a total cover value, which is sampled at a species level. Fixed-point photographs (Method 3) that use digital repeat photos from a consumer-grade digital camera are considered to be a reliable solution in this situation. This method of traditional fixed-point photography can derive cover data that can be spatially extensive and provide an objective estimate of bush encroachment, which can hence improve the quality of fractional cover modelling. Therefore, fixed-point photography provides an alternative, as it can record these changes (i.e. encroachment) as they happen over a long period, while providing consistent and accurate data.

However, this approach is time-consuming, its spatial coverage is limited and it is expensive, due to the large workforce that is required for pursuing it. According to Godinez-Alvare et al. (2009), there is no standardized method for assessing herbaceous cover, as it is difficult to conduct a comparison across space and time because of the variety of methods being used. Traditional field-based work-level data application can be difficult and problematic, not only because of the limited spatial extent, but also because the data is frequently biased, due to subjective interpretations (Meyer and Okin, 2015). Within the traditional field-based monitoring of savannah rangelands, the fixed-point photographs have gained popularity as they provide a comparable change at the sites targeted for bush control, with changes at the reference sites where the encroachment is not being controlled. Therefore, this method allows for a differentiation between the changes caused by the fluctuating precipitation and those resulting from bush encroachment control (Ward et al., 2014). Contrary to the other two methods mentioned above (Methods 1 and 2) this method did not include much of the precipitation variations. The biggest challenge of fixed-point photographs is that they have a limited aerial coverage, with limitations in the camera resolution, data storage and access). Given the spatial and temporal variability of savannah rangelands, their assessment and monitoring remains a challenge when using traditional methods. However, some researchers still argue that it is an effective and easy method for monitoring the vegetation changes annually and through the season (Ward et al., 2014).

The traditional ways of monitoring savannah rangelands over the years have managed to assess the impact of climate change and the rate of bush encroachment (Wasiolka and Blaum, 2011). According to the literature, the customary monitoring of the encroachment of savannah rangeland has revealed a relationship between bush encroachment and droughts (Angassa and Oba, 2007, 2010). These studies have found that bush encroachment is mostly exacerbated by the lack of precipitation, more especially in semi-arid and arid regions. IPCC (2014) released projections which suggested that there will be a general decrease in the precipitation, coupled with increased an spatial and temporal variability and the occurrence of frequent droughts in the regional climate in southern Africa. The projections of this model stated that climate change could have pivotal implications on the persistence of bush encroachment in the savannah rangelands. Subsequently, numerous studies have focused on the spatial distribution and dynamics of the bush encroachment phenomenon by using projected climate change scenarios, which could be useful in generating important information for management purposes (Shekede et al., 2018). The assessment and monitoring of rangelands is therefore important for providing much-needed information on the vegetation conditions (Thackway et al., 2006). To date, several research studies have been conducted on monitoring the impacts of climate change and bush encroachment in savannah rangelands (Paudel and Andersen, 2010; Angassa, 2014) by using the abovementioned methods. Traditional monitoring remains crucial only for ground-truthing, and not for the assessment itself, and the technological advancements should be deployed at an optimal level.

### *5.2. Monitoring change and assessment in bush encroachment coverage using remote sensing*

When compared to the traditional approaches, remote sensing data provide a better alternative for natural resource management, due to their capacity to provide a synoptic view. Repeating the coverage sensing is an effective tool for assessing rangeland vegetation and other surface attributes quickly and accurately. The evidence shows that remote sensing may be preferable to the traditional ground measuring methods for the following reasons: (1) It promotes broad data gathering by lowering the monitoring labour requirement; (2) it lowers human bias by limiting the effect of human judgment; (3) it is more precise; and (4) it provides a permanent record of the information, which can be preserved for future study (Boswell et al., 2017). The data collection and interpretation of remote sensing varies across the spectrum, as it involves different techniques for assessing and monitoring savannah rangelands. For example, the aerial photography technique photographs the earth's surface, or features of its atmosphere, with cameras that are mounted on aircraft, helicopters, UAVs, balloons or other aerial methods (data collection). The aerial photographs are available at different scales, for example 1:20 000, and they provide historical data of the long-term changes in the tree-grass dynamics. The analysis and interpretation of aerial photography follows a systematic approach, from a general to a specific interpretation. This involves both the detection and identification of a feature by using digital processes. Meanwhile, satellite images can be obtained from a freely-available website, such as http://landsat.usgs.gov/, and some (images) can be bought from various sources, such as https://earth.esa.int. Because remote sensing data is available in a digital format, it may be processed and analyzed by using a computer. As a preliminary to visual interpretation, digital processing can be employed to enhance the data.

The use of aerial photography in the ecological world during the mid-20th century showed that the phenomenon of bush encroachment had occurred in many savannah rangelands on the African continent (Shantz and Turner, 1958). Aerial photography provided a better alternative to the traditional field-based assessment of rangelands, as it was computer-based and cartographic methods were usually used to study a landscape. It has been proven to be spatially extensive and provides an objective estimate of bush encroachment over the years (Rohde and Hoffman, 2012; Shekede et al., 2018). This method has also been used to investigate the causes of bush encroachment and it has yielded successful results (Wigley et al., 2009; Rohde and Hoffman, 2012; Shekede et al., 2018;

Scott et al., 2017). Wigley et al. (2009) used aerial photography to study the effects of three main land-use practices in the South African savannah rangelands, namely, the communal activities, commercial activities and conservation, and their effects on the process of bush encroachment. The study found that all three land-use practice systems were affected by bush encroachment, but it was perceived to be most beneficial by the commercial and conservation land users. Aerial photographs provide researchers with images with a high resolution and spatiotemporal resolution, which assert the intensity dominant scale approach and provide a robust method of characterising bush encroachment (Scott et al., 2017; Shekede et al., 2018). Aerial photography-derived cover data can be spatially extensive, can provide an objective estimate of bush encroachment and can hence improve the quality of fractional cover modelling on a satellite pixel scale.

Aerial photography gives an overview of the rate of encroachment by detecting the direction and magnitude of change, and it is mostly based on the interpretation of historical repeat photography (Hudak and Wessman, 1998; Masocha et al., 2017). The remotely-sensed data from aerial photographs provide more comprehensive information (images of 15–30M resolution) for determining the landscape and assessing the pattern of ecological changes in an area of interest (Rango et al., 2009). Although the use of aerial photography is computer-based, it still requires some fieldwork in order to provide valuable insights into the patterns that have been observed and measured (Lubetkin et al., 2017). Fine-scale resolution aerial photograph imagery is used to detect spatial variations in savannah rangelands and the cyclic patterns of the ecosystems, as well as where the high variations are present. Laliberte and Rango et al. (2009) stated that hyperspatial imagery allows for the quantification of vegetation cover relative to a patch size, as well as the composition and structure of bare soil, at multiple spatial scales. Recent research has shown that the land cover categorization of woody vegetation may be estimated as a proportion of aerial picture pixels classified as woody vegetation in each satellite pixel's spatial range. (Ludwig et al., 2019).

Aerial photography could only be deployed at individual locations (O'Connor et al., 2014) until Graw et al. (2017) conducted a national-level analysis. As many studies focused only on local regions, this study aimed to make a wide-scale assessment, by using high-resolution aerial photography data. The study used supervised classification, which is linked to the field-based data of bush encroachment and to the respective pixels of multi-scale remotely-sensed data. According to Graw et al. (2017), the study managed to identify areas of bush encroachment based on their preconditions, such as variations in the rainfall and the intensity of cattle grazing. The most difficult aspect of this approach is to understand the drivers of change, which is also emerging in the fields of ecology and remote sensing.

Like every tool or method, the use of aerial photography has its limitations. The most difficult aspect of this approach is to understand the drivers of change, such as climate variability, as well as the emerging ecology and remote sensing fields. According to Shekede et al. (2015), this approach has been proven to be difficult to detect when using the available techniques, such as the visual interpretation of aerial photographs. For example, an increase in the intensity could be interpreted as being indicative of the thickening of woody patches, which increases the degree of contrast of the spatial heterogeneity in a landscape. Furthermore, Shekede et al. (2015) stated that the textural analyses of multi-temporal imagery, or the post-classification comparison of time-series, can be difficult when using the available methods of aerial photographs i.e. visual interpretation. While other techniques have enabled the determination of the location and size of woody plant clusters, they have often failed to determine the scale at which the encroachment occurs.

Repeat photography sets the foundation for satellite imagery; therefore, it has played a pivotal role in history. Advances in earth observation technology have produced innovative remote sensors (e.g. Landsat 8 OLI MODIS, SPOT-image etc.), which provide new opportunities that are considered to be valuable for monitoring the state of the environment (Ludwig et al., 2016; Worku, 2018). For example, satellites such as Landsat offer unparalleled archives of free, radiometrically-correct, high-resolution data that date back to the early 1970s. This provides researchers with discriminate data at various spatial, temporal and spectral resolutions. These sensors have broken through many of the challenges that researchers have encountered when using field-based or aerial photographs. For example, using such technologies for the mapping and monitoring of bush encroachment over a large area has proved to be successful (Dube and Mutanga, 2015). The use of multitemporal imagery has had a positive outcome for distinguishing between the native tree species and invasive species, by identifying the differences in leaf phenology of the encroacher species. Researchers have made use of remote sensors, such as the Advanced Very High-Resolution Radiometer (AVHRR) or the Moderate Resolution Image Spectroradiometer (MODIS) (Ponce-Campos et al., 2013) to map fractions of the bush encroachment. The use of multi-resolution methods to map the fractional cover of encroachment growth formed at a sub-pixel level, aims to improve the mapping of land cover in African savannah rangelands, grasslands and shrubland biomes. Therefore, this study found that rangeland ecosystems have an intrinsic system sensitivity to water availability (variations in rainfall). In addition, during the dry season, the optical bands (MODIS) alone can map the fraction of bush encroachment with an 80% balanced accuracy.

It is worth noting that remotely-sensed data from MODIS (250 km) and AVHRR (1 km) have been used in the field of ecology and management, in order to understand how vegetation production responds to climate change; they have therefore resolved the knowledge gap built on course resolution. As much as the remotely-sensed data can give a large-scale overview across the landscapes, the need for fieldwork remains a pivotal factor for the calibration, management and validation (reference data) of the results that are obtained (Rameleo et al., 2018). Vogel and Strohbach (2009) stated that the application of hypertemporal data, such as MODIS or AVHRR, does not provide sufficient spatial resolution to detect the local changes that are relevant for rangeland managers and for different rangeland management practices e.g. in communal and commercial areas. According to Jansen et al. (2018), the most- used satellites in rangeland management are Landsat and MODIS; however, Landsat data are preferred over those from MODIS, as they provide a longer continuous dataset and have a 30 m resolution, which is more appropriate for mapping (Luwdig et al., 2019), for the estimation of biomass (Dube et al., 2019) or rangeland vegetation and for assessing distinct management areas (Jansen et al., 2018).

Over the past few decades, several different approaches have been implemented, using different remote sensing data, such as SPOT

5, Landsat TM, Moderate Resolution Imaging Spectroradiometer (MODIS), the Advanced Very High-Resolution Radiometer (AVHRR) and the Normalized Difference Vegetation Index (NDVI), to examine the effects of precipitation variability on bush encroachment. Numerous studies have investigated the competitive interaction between encroaching plants and herbaceous layers by measuring the water intake of the different vegetation forms (Munyati et al., 2011; O'Connor et al., 2014). While some research studies have determined the precipitation requirements for bush encroachment and the establishment of specific plants (Shezi et al., 2021), others have tried to examine and correlate the climatic records with the bush encroachment density (O'Connor et al., 2014; Munyati et al., 2011).

Over the past two decades, remotely-sensed data have been used to derive the spatial patterns in savannah rangelands that have a high grazing pressure and high precipitation variability (Paudel and Andersen, 2010; Graw et al., 2017). Numerous research studies have used different vegetation indices, such as NDVI and LAI, as well as the phenology characteristics that allow the discrimination of vegetation at a species-level, based on the spectral signature (Bunting et al., 2019; Dube et al., 2019). The literature shows that a limited number of studies, for example, Paudel and Andersen (2010), Liao et al. (2018) and Kgosikoma et al. (2012), included the effects of rainfall variability and gradient, while other studies, for example, Dube and Nhamo (2020) did not include the gradient, which removes the effects of landscape variability. Comparative research is also relevant, as it seeks to examine the rate of bush encroachment in protected and unprotected rangelands under climate variability.

## 6. Application of remote sensing relating to the effects of climate variability on bush encroachment

As the world changes and becomes more industrialized, so does the natural environment. The threats facing the savannah rangelands have also increased, as some of the pressures (threats), whether they are direct or indirect, have intensified as time has progressed. Factors, such as the precipitation, atmospheric pollution and grazing gradient, need continuous assessment, as they occur over a long period, and providing consistent and accurate data by using traditional fieldwork surveys is difficult, as mentioned above. Several researchers have highlighted the importance of deploying such a tool, whether it is to investigate erosion (Maestre et al., 2016), the impact of communal grazing on savannah rangelands in arid areas or the resettlement in Ethiopia (Hudak, 1999; James et al., 2003).

This approach is important for application in rangeland areas, for monitoring the changes in vegetation cover, grazing management and remedial treatment effectiveness (Godinez-Alvare et al., 2009; Masocha et al., 2017). It can also be implemented at different radiometric and spatial resolutions, as long as the spatial scale of the process is greater than the pixel size (Shekede et al., 2015; Stafford et al., 2017). The panchromatic aerial photographs with a low spectral and radiometric resolution had a low capability of detecting the fine-scale differences that reflect the degree of contrast in a landscape (Shekede et al., 2015). In every field of study, there are always critics;, some have pointed out that aerial photography can only be deployed at individual locations (O'Connor et al., 2014), but Skowno et al. (2017) proved them wrong, when he conducted a national-level analysis.

Over the past decade, studies have implemented the use of GIS and remote sensing to gain a better understanding of bush encroachment (Dougill and Trodd, 1999; Musa and Shaib, 2010; Maestre et al., 2016). Earth observation technologies have produced innovative remote sensors that provide valuable new opportunities in the context of monitoring bush encroachment in the rangelands (Shoko et al., 2019; Ludwig et al., 2016; Dube and Mutanga, 2015). The primary objective in such remote sensing studies of bush encroachment is to map and quantify the areas that are affected by the phenomenon (Hudak and Brockett, 2004; Parente et al., 2019). The historical imagery in archived multitemporal remotely-sensed data offers a wide range of possibilities for the management of rangelands (Munyati et al., 2011; Keno and Suryabhagavan, 2014). Several studies have used multispectral satellites or sensors to monitor (detect and map) the rate of bush encroachment (Symeonakis and Higginbottom, 2014; Graw et al., 2017).

The approach used for accurately assessing bush encroachment in a large-scale savannah rangeland with satellite imagery remains a daunting task, because of the vegetation variability in response to high variations in the precipitation patterns, which might obscure the underlying degradation processes. For example, the classification deployed in satellite images for detecting and managing encroachment is varied, with fluctuating classification accuracies (Munyati et al., 2011). One of the factors that makes the discrimination of vegetation daunting in savannah rangelands is the low chlorophyll content during the senescent stage, which reduces the red to near-infrared (NIR) spectral contrast, which results in the impaired ability to distinguish vegetation from bare paths of soil (Sibanda et al., 2016; Madonsela et al., 2017). The encroaching woody species can be easily classified as greening by some satellite sensors, if it occurs during the greening of grass cover (herbaceous layer), especially during the rainy season.

The use of the red, near-infrared (NIR) and shortwave infrared (SWIR) wavelengths, which are more sensitive to vegetation changes, has enhanced the spectral products used for vegetation discrimination (Higginbottom et al., 2018). These advanced analyses have demonstrated the move from the static, bi-temporal measures of change toward a more continuous time-series analysis (Venter et al., 2018) in areas such as phenology (Ludwig et al., 2019), land cover change (Gong et al., 2019; Royimani et al., 2019a) and woody plant encroachment (Venter et al., 2018). These studies have provided a valuable insight into the distinct advantages of the low-resolution regional measurement of vegetation trends (greening and browning) and the causes of vegetation degradation. Many studies have identified the degradation of rangelands by using different satellite sensors to focus on distinguishing between the climate and human-driven bush encroachment rates (Symeonakis et al., 2016; Baumann et al., 2018; Bunting et al., 2019).

Until recently, the previous pixel-based Bayesian approaches were the most commonly-applied land cover classification techniques for bush-encroached areas; however, most current studies are applying machine learning algorithms, which include Classification Trees (CT), Artificial Neural Networks (ANN), Support Vector Machines (SVM) and Random Forest (RF), among others, which are far more efficient (Rodriguez-Galiano et al., 2015; Symeonakis and Higginbottom, 2014). The application of hypertemporal data, such as MODIS or AVHRR, does not provide sufficient spatial resolution to detect local changes that are relevant for rangelands managers, in both communal or commercial areas (Vogel and Strohbach, 2009; Shekede et al., 2015). The application of fine spatial resolution imagery to detect fine-scale spatial variations in savannah rangelands has identified cyclic patterns of vegetation, as well as locations where there are high variations of bush encroachment (Parente et al., 2019; Shoko et al., 2019). Remotely-sensed data have provided accurate and continuous vegetation data over the years.

The multispectral and hyperspectral sensors that have been launched recently are expected to provide a synoptic view of the rangelands and valuable data at a spatial and temporal scale, which were unattainable by using the old generation of broadband sensors (Sibanda et al., 2016; Adelabu and Dube, 2015). Some research studies have made use of SPOT 5 HRG multispectral imagery and concluded that it is more applicable for integration with a comparable band, such as Multispectral Instrument (MSI) imagery, for mapping bush encroachment cover in a multitemporal analysis (Graw et al., 2017). Munyati et al. (2011) showed that Landsat 8 OLI sensor imagery is more applicable or suitable for densely-encroached areas than High-Resolution Geometric (HRG) images, due to its higher radiometric sensitivity, which permits the monitoring of physiology-related woody reflectance.

Furthermore, the Landsat 8 OLI sensor provides an improved radiometric resolution, which increases the spectral record precision and eliminates the spectral saturation of the sensor (Graw et al., 2017). The refined spectral ranges across the near-infrared (NIR) and panchromatic bands have improved the radiometric resolution of the Landsat 8 OLI sensor from 8 bits to 12 bits, which has enabled the perilous characterisation of different forms of vegetation (Dube and Mutanga, 2015). The narrow NIR band also prevents water absorption, which allows the acquisition of an accurate surface reflectance. Literature has shown that the application of hyperspectral data from the available sensors has yielded high accuracies in dominant grass discrimination, ranging from 70% to 99% (Shoko et al., 2019; Naidoo et al., 2012), when compared to multispectral sensors (Shoko and Mutanga, 2017a). For example, Naidoo et al. (2012) showed that the bush encroachment component (woody) in savannah rangelands decreases the temporal variation within the NDVI signal, as the shrubs maintain their leaves throughout the dry season.

In South Africa, satellite-derived vegetation has been used to assess, monitor and map bush encroachment. Some scholars have studied the monitoring of land degradation and restoration (Symeonakis et al., 2016), bush encroachment detection in Africa (Graw et al., 2017), rangeland productivity (Kavwele et al., 2017; Borhara et al., 2020), the monitoring of bush encroachment in savannah regions (Symeonakis and Higginbottom, 2014), climate change and adaptive land management in southern Africa (Ramoelo et al., 2018), mapping the fraction of woody cover in semi-arid savannahs by using multi-seasonal composites from Landsat data (Higginbottom et al., 2018) and assessing the Leaf Area Index in tropical savanna rangelands (Dube et al., 2019), to name a few. Very limited, or no literature, exists on the impact of bush encroachment, coupled with climate variability, in protected and unprotected areas in savannah rangelands (comparative studies). There is still a huge gap that remains to be explored; for example, comparing the rangelands under different management systems within the same areas and the linkage of the rate of bush encroachment that exists in each system i.e. in the communal and private areas.

## 7. Summary

The literature has shown that once bush encroachment has been established, it accelerates the decline in grass cover, while the intensification of the climate change effects, such as droughts, makes it difficult for the savannah rangeland to recover. The eastern part of Africa has experienced a 90% reduction in its savannah rangeland for grazing, which has been eliminated by the bush cover (Bikila et al., 2016; Angassa and Oba, 2010). Previous research studies have affirmed the statement that it is difficult to separate some of the causes of bush encroachment, such as overgrazing and episodic rainfall or fires, which have shifted the savannah rangeland by >30% to <10%, respectively (Angassa and Oba, 2007; Andreu et al., 2019; Kgosikoma et al., 2012).

It was noted in the literature that savannah rangelands in southern Africa experience a substantial precipitation variability in the short- to medium-term, which makes them highly resilient (Wasiolka and Blaum, 2011; Dube and Pickup, 2001). Therefore, Axelsson and Hanan (2017) suggested that the amount and frequency of rainfall may play a key role in the occurrence of bush encroachment, because trees require more rain to germinate than do grasses, and they may germinate in large numbers, with or without grazing, in rare and high rainfall years. Local disturbances and management also have a far greater impact on bush encroachment than global drivers, such as rainfall patterns or variability (Ponce-Campos et al., 2013; Venter et al., 2018). Higginbottom et al. (2018) noted that arid rangeland ecosystems show more variability in response to both natural and anthropogenic disturbances. Some studies have suggested that it is difficult to separate the anthropogenic impacts from the natural processes, such as seasonal changes (droughts and rainfall) and fire, when interpreting the changes in vegetation cover (Bunting et al., 2019; Naidoo et al., 2012).

Although ample research has been conducted on the impact of climate change and variability, it has been observed that the studies have omitted the issue of seasonality. Seasonal variations also play a role in the intensity and impact of overgrazing between the wet and dry seasons; typically, the rangelands that are used during the long dry season and drought years are easily encroached. Although these studies have broadened the understanding and scope of the bush encroachment phenomenon, from its impact on the ecology to its impact on carbon sequestration (Stafford et al., 2017), there has been no correlation between bush encroachment and climate variability in rangeland areas, especially by using remotely-sensed data. However, some studies have used remote sensing to compare the biodiversity between the protected savannah rangeland and the adjacent non-protected farmland in the southern Kalahari (Munyati et al., 2011; Mutunga, 2018). There are some gaps that still need to be explored with regard to the impact of climate variability on rangeland bush encroachment, especially in southern Africa.

A healthy rangeland ecosystem is pivotal for Africa's economy because of its revenue-earning role for the provision of rural livelihoods (the sustenance of livestock through grazing) and game ranches (game viewing) (Dean and MacDonald, 1994; Munyati et al. (2011). The restoration and monitoring of rangelands are important because of the economic value that can be attached to savannah rangelands, such as tourism, commercial activities and smallholder livestock production systems (Andreu et al., 2019). These economic activities can significantly elevate the poverty line of the rural communities. Savannah rangelands can potentially benefit the global carbon budget, and their effect on the disadvantaged communal areas (rural livelihoods) has encouraged considerable government investment into the clearing of these alien and native invasive woody plants (Thondhlana and Muchapondwa, 2014); for example, South Africa invests approximately 100 million US$ per annum in this venture (Venter et al., 2018).

The phenomenon of bush encroachment has been widely researched in Ethiopia over the past four decades (Angassa and Oba, 2007; Angassa, 2014). It was found that climate variation has a huge impact on the state of the savannah rangeland in both protected and unprotected areas. The rangeland in Ethiopia covers between 61% and 65% of the total area of the country, of which 19% has been declared to be severely encroached by woody species (Abate and Angassa, 2016). The literature has shown that the application of remotely-sensed data in Ethiopia, by using multispectral sensors and vegetation indices, such as NDVI, has proven to be effective for classifying the different vegetation types, because of the high variations in its climate, soil characteristics and management conditions (Keno and Suryabhagavan, 2014; Kabeta et al., 2020). The high variations in the vegetation and bush encroachment rate are associated with the arid and semi-arid climatic conditions in the country, which are relatively harsh, and with the low, unreliable and erratic rainfall (Angassa, 2014). The literature shows, for example, it that in East Africa, the Kenyan side had a much higher rate of bush encroachment, compared to that in neighbouring Ethiopia.

In most African countries, particularly in East Africa, the terrestrial ecosystems are shaped by the long-term interaction between climate variability and the changes in human activities. The sustainability of savannah rangelands in East Africa is primarily threatened by the climate (rainfall patterns), the land-use changes and forage availability in both the protected and unprotected areas. Given the observed trends in precipitation seasonality, droughts and land use in East African countries, this is expected to change in the future; therefore, monitoring techniques, such as the deployment of hyperspectral and multispectral sensors, are used to improve our understanding of the potential impacts of land-use changes on the ecosystem services in the East African rangelands. It has been observed that Kenya has a high rate (39%) of bush encroachment in the rangeland areas, with the severe impact being felt in both the protected and unprotected areas, which changes the livestock grazing habits and conservation benefits (Mutunga, 2017, 2018).

A substantial amount of literature shows that bush encroachment is a major challenge in southern Africa and that it continues to be a problem to this day. For example, it has increased rapidly in Namibia to an estimated 32% in both the protected and unprotected areas (Kgosikoma et al., 2012). Stafford et al. (2017) noted that 50% of the protected savannah rangeland areas in Namibia are believed to be encroached by bush and that most of these areas receive about 300–500 mm of rainfall annually (Ponce-Campos et al., 2013; Bikila et al., 2016). Hudak and Brockett (2004) cited that the traditional understanding of the regional drivers of the bush encroachment phenomenon in Namibia are the prolonged denudation of soils caused by drought and grazing pressure, coupled with above-average precipitation, which favours mass shrub growth. The application of optical remote sensing in Namibia has broadened the understanding of bush encroachment, more especially on a regional and local scale, as researchers have mapped the wood cover changes (Skowno et al., 2017). Some of the remote sensing sensors that set the foundation included the coarse resolution products derived from MODIS and SPOT VGT data, which did not provide the spatial resolution required to monitor bush encroachment. This led researchers to experiment with a variety of sensors, including the Synthetic Aperture Radar (SAR), satellite data (Advanced Land Observing Satellite (ALOS), Phased Arrayed L-band Synthetic Aperture Radar (PALSAR) and Landsat 8 OLI, in order to gain a knowledge about monitoring systems.

Some studies in the literature looked at the effects of climate change, coupled with the driver trends of bush encroachment and the inter-annual variability of the global carbon sink, depending on the climatic region, by using the remotely-sensed data (Parente et al., 2019). In addition, Buntinga et al. (2019) assessed the responses of different plant communities to the climate in arid and semi-arid regions, using remote sensing, by looking at their seasonal patterns. Botswana used remotely-sensed data to derive spatial patterns in the land-use intensity (arising from humans) and changes in rainfall variability in areas of communal and semi-commercial grazing (Dube and Pickup, 2001; Tastad et al., 2010). Munyati et al. (2011) used remotely-sensed data to monitor the deterioration of savannah rangeland caused by the encroachment of bush in communal (unprotected) and conservation rangelands (protected), but they did not include the influence of climate variability, particularly rainfall. Wigley et al. (2009) conducted a study on the effects of three main land-use practices in the South African savannah rangelands, namely communal, commercial and conservation, on the processes of bush encroachment by using aerial photography, and it was noted that all three were affected by bush encroachment. It was perceived to be the most beneficial for the commercial and conservation land users.

## 8. Conclusions

The changing precipitation patterns over time illustrate that rainfall variability influences vegetation cover and bush encroachment. Therefore, investigations into the influence of climate variability on bush encroachment, in both protected and non-protected areas, by using remotely sensed data, remains vital. Models of the response and feedback to climate change and land cover variability need to reflect both processes, more especially the remotely-sensed data. Although several studies have linked bush encroachment with the pressure of heavy grazing, wildlife and the effects of climate change, the implications of climate variability are poorly understood. The literature has demonstrated that the mapping of the encroachment phenomenon is a challenging approach, due to its temporal and spatial variability. Regardless of the above, the understanding of how climate variability and change impact the protected and unprotected areas is still limited, due to the scanty, and sometimes fragmented, research, especially with regard to the use of remote sensing technology. It is worth noting that other studies have looked at the effects of climate change and variability on national parks and private reserves, but they did not make use of remote sensing. A gap still exists in the classification of bush encroachment, and there is an urgent need to investigate the influence of climate variability on bush encroachment, in both protected and non-protected areas. It has been observed in the literature that some of these triggers of bush encroachment are interconnected and that one of them can lead to a chain of events that fuels encroachment. For example, uncontrolled grazing (overgrazing), which is linked to the effects of climate change (severe drought), can lead to the deterioration of soil fertility, soil erosion and the depletion of biodiversity.

## 9. The limitations and possible future direction

Because climate variability and change, as well as the grazing density, account for the majority of the changes in woody cover, future research must include all of these factors. The status of bush encroachment can be used to assess the long-term viability of cattle and wildlife grazing on rangelands, in both protected and unprotected locations; therefore, future research must be done in this area. The dominant scales observed are constrained by the spatial scope of our study area, as well as the characteristics of the multi-temporal datasets used and the aerial photographs and satellite images used in the various studies spanning four decades.

## Statement of ethics

Comments

1. Human subjects are not included in the review of this study.
2. No permission for data usage the study.
3. Research activities are restricted to those detailed in the review.
4. The research team comply with conditions outlined in AppSci/ASFREC/2015/1.1 v1, CODE OF ETHICS, ETHICAL VALUES AND GUIDELINES FOR RESEARCHERS.

## 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.

## References


Abate, T., Angassa, A., 2016. Conversion of savanna rangelands to bush dominated landscape in Borana, Southern Ethiopia. Ecol. Process. 5 (1), 1–18.

Adelabu, S., Dube, T., 2015. Employing ground and satellite-based QuickBird data and random forest to discriminate five tree species in a Southern African Woodland. Geocarto Int. 30 (4), 457–471.

Andreu, A., Dube, T., Nieto, H., Mudau, A.E., González-Dugo, M.P., Guzinski, R., Hülsmann, S., 2019. Remote sensing of water use and water stress in the African savanna ecosystem at local scale–Development and validation of a monitoring tool. Phys. Chem. Earth 112, 154–164. Parts A/B/C.

Angassa, A., 2005. The ecological impact of bush encroachment on the yield of grasses in Borana rangeland ecosystem. Afr. J. Ecol. 43 (1), 14–20.

Angassa, A., 2014. Effects of grazing intensity and bush encroachment on herbaceous species and rangeland condition in southern Ethiopia. Land Degrad. Dev. 25 (5), 438–451.

Angassa, A., Oba, G., 2007. Relating long-term rainfall variability to cattle population dynamics in communal rangelands and a government ranch in southern Ethiopia. Agric. Syst. 94 (3), 715–725.

Angassa, A., Oba, G., 2008. Herder perceptions on impacts of range enclosures, crop farming, fire ban and bush encroachment on the rangelands of Borana, Southern Ethiopia. Hum. Ecol. 36 (2), 201–215.

Angassa, A., Oba, G., 2010. Effects of grazing pressure, age of enclosures and seasonality on bush cover dynamics and vegetation composition in southern Ethiopia. J. Arid Environ. 74 (1), 111–120.

Angassa, A., Oba, G., Treydte, A.C., Weladji, R.B., 2010. Role of traditional enclosures on the diversity of herbaceous vegetation in a semi-arid rangeland, southern Ethiopia. Livest. Res. Rural Dev. 22 (9).

Archer, S.R., Davies, K.W., Fulbright, T.E., McDaniel, K.C., Wilcox, B.P., Predick, K.I., Briske, D.D., 2011. Brush Management as a Rangeland Conservation Strategy: a Critical Evaluation. Conservation Benefits of Rangeland Practices. US Department of Agriculture Natural Resources Conservation Service, Washington, DC, USA, pp. 105–170.

Arntzen, J., 1998. Economic Valuation of Communal Rangelands in Botswana: A Case Study. CREED.

Axelsson, C.R., Hanan, N.P., 2017. Patterns in woody vegetation structure across African savannas. Biogeosciences 14 (13), 3239–3252.

Baumann, M., Levers, C., Macchi, L., Bluhm, H., Waske, B., Gasparri, N.I., Kuemmerle, T., 2018. Mapping continuous fields of tree and shrub cover across the Gran Chaco using Landsat 8 and Sentinel-1 data. Rem. Sens. Environ. 216, 201–211.

Belayneh, A., Tessema, Z.K., 2017. Mechanisms of bush encroachment and its inter-connection with rangeland degradation in semi-arid African ecosystems: a review. J. Arid Land 9 (2), 299–312.

Bikila, N.G., Tessema, Z.K., Abule, E.G., 2016. Carbon sequestration potentials of semi-arid rangelands under traditional management practices in Borana, Southern Ethiopia. Agric. Ecosyst. Environ. 223, 108–114.

Borhara, K., Pokharel, B., Bean, B., Deng, L., Wang, S.Y.S., 2020. On Tanzania's precipitation climatology, variability, and future projection. Climate 8 (2), 34.

Boswell, A., Petersen, S., Roundy, B., Jensen, R., Summers, D., Hulet, A., 2017. Rangeland monitoring using remote sensing: comparison of cover estimates from field measurements and image analysis. AIMS Environ. Sci. 4 (1), 1–16.

Bunting, E.L., Munson, S.M., Bradford, J.B., 2019. Assessing plant production responses to climate across water-limited regions using Google Earth Engine. Rem. Sens. Environ. 233, 111379.

Chen, J., Yi, S., Qin, Y., Wang, X., 2016. Improving estimates of fractional vegetation cover based on UAV in alpine grassland on the Qinghai–Tibetan Plateau. Int. J. Rem. Sens. 37 (8), 1922–1936.

D'Adamo, F., Ogutu, B., Brandt, M., Schurgers, G., Dash, J., 2021. Climatic and non-climatic vegetation cover changes in the rangelands of Africa. Global Planet. Change 202, 103516.

Dean, W.R.J., Macdonald, I.A.W., 1994. Historical changes in stocking rates of domestic livestock as a measure of semi-arid and arid rangeland degradation in the Cape Province, South Africa. J. Arid Environ. 26 (3), 281–298.

Department of Environment Affairs and Tourism: White Paper on Environmental Management Policy. https://www.dffe.gov.za/sites/default/files/legislations/environemtal_management_0.pdf, July 1997.

Dougill, A.J., Akanyang, L., Perkins, J.S., Eckardt, F.D., Stringer, L.C., Favretto, N., Atlhopheng, J., Mulale, K., 2016. Land use, rangeland degradation and ecological changes in the southern Kalahari, Botswana. Afr. J. Ecol. 54 (1), 59–67.

Dube, T., Mutanga, O., 2015. Evaluating the utility of the medium-spatial resolution Landsat 8 multispectral sensor in quantifying aboveground biomass in uMgeni catchment, South Africa. ISPRS J. Photogrammetry Remote Sens. 101, 36–46.

Dube, K., Nhamo, G., 2020. Evidence and impact of climate change on South African national parks. Potential implications for tourism in the Kruger National Park. Environ. Dev. 33, 100485.

Dube, O.P., Pickup, G., 2001. Effects of rainfall variability and communal and semi-commercial grazing on land cover in southern African rangelands. Clim. Res. 17 (2), 195–208.
Dube, T., Pandit, S., Shoko, C., Ramoelo, A., Mazvimavi, D., Dalu, T., 2019. Numerical assessments of leaf area index in Tropical Savanna Rangelands, South Africa Using Landsat 8 OLI derived metrics and in-situ measurements. Rem. Sens. 11 (7), 829.
Dyksterhuis, E.J., 1949. Condition and management of range land based on quantitative ecology. J. Range Manag. 2 (3), 104–115.
Foran, B.D., Tainton, N.M., Booysen, P.D.V., 1978. The development of a method for assessing veld condition in three grassveld types in Natal. Proc. Ann. Cong. Grassland Soc. South. Afr. 13 (1), 27–33.
Godínez-Alvarez, H., Herrick, J.E., Mattocks, M., Toledo, D., Van Zee, J., 2009. Comparison of three vegetation monitoring methods: their relative utility for ecological assessment and monitoring. Ecol. Indicat. 9 (5), 1001–1008.
Graw, V., Oldenburg, C., Dubovyk, O., 2016. Bush Encroachment Mapping for Africa: Multi-Scale Analysis with Remote Sensing and GIS. ZEF-Center for Development Research University of Bonn, Discussion Paper, 218.
Gong, P., Li, X., Zhang, W., 2019. 40-Year (1978–2017) human settlement changes in China reflected by impervious surfaces from satellite remote sensing. Sci. Bull. 64 (11), 756–763.
Graw, V., Dubovyk, O., Piroska, R., 2017. July. Bush encroachment detection in Africa—A multi-scale approach. In: 2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). IEEE, pp. 4270–4273.
Higginbottom, T.P., Symeonakis, E., Meyer, H., van der Linden, S., 2018. Mapping fractional woody cover in semi-arid savannahs using multi-seasonal composites from Landsat data. ISPRS J. Photogrammetry Remote Sens. 139, 88–102.
Hudak, A.T., 1999. Rangeland mismanagement in South Africa: failure to apply ecological knowledge. Hum. Ecol. 27 (1), 55–78.
Hudak, A.T., Brockett, B.H., 2004. Mapping fire scars in a southern African savannah using Landsat imagery. Int. J. Rem. Sens. 25 (16), 3231–3243.
Hudak, A.T., Wessman, C.A., 1998. Textural analysis of historical aerial photography to characterize woody plant encroachment in South African savanna. Rem. Sens. Environ. 66 (3), 317–330.
IPCC, 2014. Summary for policymakers In- Climate Change: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. In: Field, C.B., et al. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (CambridgeCambridge, United Kingdom and New York, NY, USA,), pp. 1–32.
James, L.F., Young, J.A., Sanders, K., 2003. A new approach to monitoring rangelands. Arid Land Res. Manag. 17 (4), 319–328.
Jansen, V.S., Kolden, C.A., Schmalz, H.J., 2018. The development of near real-time biomass and cover estimates for adaptive rangeland management using Landsat 7 and Landsat 8 surface reflectance products. Rem. Sens. 10 (7), 1057.
Ji, W., Hanan, N.P., Browning, D.M., Monger, H.C., Peters, D.P.C., Bestelmeyer, B.T., Archer, S.R., Ross, W., Lind, B.M., Anchang, J., Kumar, S.S, et al., 2019. Constraints on shrub cover and shrub–shrub competition in a US southwest desert. Ecosphere. https://doi.org/10.1002/ecs2.2590.
Joubert, D.F., Rothauge, A., Smit, G.N., 2008. A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. J. Arid Environ. 72 (12), 2201–2210.
Kabeta, L., Dalle, G., Tolera, M., Kelboro, G., 2020. Bush encroachment and impacts on grass biomass in Senkelle Swayne's Hartebeest Sanctuary, Ethiopia. Biodiversity 1–10.
Kakembo, V., Ndou, N., 2019. Relating vegetation condition to grazing management systems in the central Keiskamma Catchment, Eastern Cape Province, South Africa. Land Degrad. Dev. 30 (9), 1052–1060.
Kavwele, C.M., Kinyanjui, M.J., Kimanzi, J.K., 2017. Time series monitoring of bush encroachment by Euclea divinorum in Ol Pejeta Conservancy Laikipia, Kenya. Int. J. Natl. Resour. Ecol. Manag. 2 (5), 85.
Keno, B., Suryabhagavan, K.V., 2014. Multitemporal remote sensing of landscape dynamics and pattern change in Dire district, southern Ethiopia. J. Geomat. 8 (2).
Kgosikoma, O.E., Harvie, B.A., Mojeremane, W., 2012. Bush encroachment in relation to rangeland management systems and environmental conditions in Kalahari ecosystem of Botswana. Afr. J. Agric. Res. 7 (15), 2312–2319.
Kraaij, T., Ward, D., 2006. Effects of rain, nitrogen, fire and grazing on tree recruitment and early survival in bush-encroached savanna, South Africa. Plant Ecol. 186 (2), 235–246.
Laliberte, A.S., Rango, A., Havstad, K.M., Paris, J.F., Beck, R.F., McNeely, R., Gonzalez, A.L., 2004. Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. Rem. Sens. Environ. 93 (1–2), 198–210.
Liao, C., Clark, P.E., DeGloria, S.D., 2018. Bush encroachment dynamics and rangeland management implications in southern Ethiopia. Ecol. Evol. 8 (23), 11694–11703.
Lubetkin, K.C., Westerling, A.L., Kueppers, L.M., 2017. Climate and landscape drive the pace and pattern of conifer encroachment into subalpine meadows. Ecol. Appl. 27 (6), 1876–1887.
Ludwig, A., Meyer, H., Nauss, T., 2016. Automatic classification of Google Earth images for a larger scale monitoring of bush encroachment in South Africa. Int. J. Appl. Earth Obs. Geoinf. 50, 89–94.
Ludwig, M., Morgenthal, T., Detsch, F., Higginbottom, T.P., Valdes, M.L., Nauß, T., Meyer, H., 2019. Machine learning and multi-sensor based modelling of woody vegetation in the Molopo Area, South Africa. Rem. Sens. Environ. 222, 195–203.
Madonsela, S., Cho, M.A., Mathieu, R., Mutanga, O., Ramoelo, A., Kaszta, Ż., Van De Kerchove, R., Wolff, E., 2017. Multi-phenology WorldView-2 imagery improves remote sensing of savannah tree species. Int. J. Appl. Earth Obs. Geoinf. 58, 65–73.
Maestre, F.T., Eldridge, D.J., Soliveres, S., Kéfi, S., Delgado-Baquerizo, M., Bowker, M.A., García-Palacios, P., Gaitán, J., Gallardo, A., Lázaro, R., Berdugo, M., 2016. Structure and functioning of dryland ecosystems in a changing world. Annu. Rev. Ecol. Evol. Systemat. 47, 215–237.
Masocha, M., Dube, T., Skidmore, A., Holmgren, M., Prins, H., 2017. Assessing effect of rainfall on rate of alien shrub expansion in a southern African savanna. Afr. J. Range Forage Sci. 34 (1), 39–44.
Meyer, T., Okin, G.S., 2015. Evaluation of spectral unmixing techniques using MODIS in a structurally complex savanna environment for retrieval of green vegetation, nonphotosynthetic vegetation, and soil fractional cover. Rem. Sens. Environ. 161, 122–130.
Muchapondwa, E., Stage, J., 2013. The economic impacts of tourism in Botswana, Namibia and South Africa: is poverty subsiding? May Nat. Resour. Forum 37 (No. 2), 80–89.
Mudongo, E.I., Fusi, T., Fynn, R.W., Bonyongo, M.C., 2016. The role of cattle grazing management on perennial grass and woody vegetation cover in semiarid rangelands: insights from two case studies in the Botswana Kalahari. Rangelands 38 (5), 285–291.
Munyati, C., Makgale, D., 2009. Multitemporal Landsat TM imagery analysis for mapping and quantifying degraded rangeland in the Bahurutshe communal grazing lands, South Africa. Int. J. Rem. Sens. 30 (14), 3649–3668.
Munyati, C., Sinthumule, N.I., 2016. Change in woody cover at representative sites in the Kruger National Park, South Africa, based on historical imagery. SpringerPlus 5 (1), 1–23.
Munyati, C., Shaker, P., Phasha, M.G., 2011. Using remotely sensed imagery to monitor savanna rangeland deterioration through woody plant proliferation: a case study from communal and biodiversity conservation rangeland sites in Mokopane, South Africa. Environ. Monit. Assess. 176 (1), 293–311.
Musa, H.D., Shaib, B., 2010. Integrated remote sensing approach to desertification monitoring in the crop-rangeland area of Yobe State, Nigeria. J. Sustain. Dev. Afr. 12 (5), 236–250.
Mutunga, K.C., 2017. Time Series Monitoring of Bush Encroachment by Euclea divinorum in Ol Pejeta Conservancy Laikipia. Kenya.
Mutunga, K.C., 2018. *Impacts of Bush Encroachment by Euclea divinorum on Wildlife Species Diversity and* Composition in Ol Pejeta Conservancy in Laikipia. Kenya (Doctoral dissertation).
Naidoo, L., Cho, M.A., Mathieu, R., Asner, G., 2012. Classification of savanna tree species, in the Greater Kruger National Park region, by integrating hyperspectral and LiDAR data in a Random Forest data mining environment. ISPRS J. Photogrammetry Remote Sens. 69, 167–179.
O'Connor, T.G., Puttick, J.R., Hoffman, M.T., 2014. Bush encroachment in southern Africa: changes and causes. Afr. J. Range Forage Sci. 31 (2), 67–88.

Oldeland, J., Dorigo, W., Wesuls, D., Jürgens, N., 2010. Mapping bush encroaching species by seasonal differences in hyperspectral imagery. Rem. Sens. 2 (6), 1416–1438.
O'Connor, T.G., Goodman, P.S., Clegg, B., 2007. A functional hypothesis of the threat of local extirpation of woody plant species by elephant in Africa. Biol. Conserv. 136 (3), 329–345.
Palmer, A.R., Bennett, J.E., 2013. Degradation of communal rangelands in South Africa: towards an improved understanding to inform policy. Afr. J. Range Forage Sci. 30 (1–2), 57–63.
Parente, L., Mesquita, V., Miziara, F., Baumann, L., Ferreira, L., 2019. Assessing the pasturelands and livestock dynamics in Brazil, from 1985 to 2017: A novel approach based on high spatial resolution imagery and Google Earth Engine cloud computing. Rem. Sens. Environ. 232, 111301.
Paudel, K.P., Andersen, P., 2010. Assessing rangeland degradation using multi temporal satellite images and grazing pressure surface model in Upper Mustang, Trans Himalaya, Nepal. Rem. Sens. Environ. 114 (8), 1845–1855.
Piao, S., Nan, H., Huntingford, C., Ciais, P., Friedlingstein, P., Sitch, S., Peng, S., Ahlström, A., Canadell, J.G., Cong, N., Levis, S., 2014. Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity. Nat. Commun. 5 (1), 1–7.
Ponce-Campos, G.E., Moran, M.S., Huete, A., Zhang, Y., Bresloff, C., Huxman, T.E., Eamus, D., Bosch, D.D., Buda, A.R., Gunter, S.A., Scalley, T.H., 2013. Ecosystem resilience despite large-scale altered hydroclimatic conditions. Nature 494 (7437), 349–352.
Ramoelo, A., Stolter, C., Joubert, D., Cho, M.A., Groengroeft, A., Madibela, O.R., Zimmermann, I., Pringle, H., 2018. Rangeland Monitoring and Assessment: a Review.
Rango, A., Laliberte, A., Herrick, J.E., Winters, C., Havstad, K., Steele, C., Browning, D., 2009. Unmanned aerial vehicle-based remote sensing for rangeland assessment, monitoring, and management. J. Appl. Remote Sens. 3 (1), 33542.
Rodriguez-Galiano, V., Sanchez-Castillo, M., Chica-Olmo, M., Chica-Rivas, M.J.O.G.R., 2015. Machine learning predictive models for mineral prospectivity: An evaluation of neural networks, random forest, regression trees and support vector machines. Ore Geol. Rev. 71, 804–818.
Rohde, R.F., Hoffman, M.T., 2012. The historical ecology of Namibian rangelands: vegetation change since 1876 in response to local and global drivers. Sci. Total Environ. 416, 276–288.
Royimani, L., Mutanga, O., Odindi, J., Dube, T., Matongera, T.N., 2019a. Advancements in satellite remote sensing for mapping and monitoring of alien invasive plant species (AIPs). Phys. Chem. Earth 112, 237–245. Parts A/B/C.
Sala, O.E., Paruelo, J.M., 1997. Ecosystem services in grasslands. In: Nature's services: Societal dependence on natural ecosystems, pp. 237–251.
Sankaran, M., Ratnam, J., Hanan, N., 2008. Woody cover in African savannas: the role of resources, fire and herbivory. Global Ecol. Biogeogr. 17 (2), 236–245.
Scholes, R.J., Archer, S.R., 1997. Tree-grass interactions in savannas. Annu. Rev. Ecol. Systemat. 28 (1), 517–544.
Scholtz, R., Polo, J.A., Tanner, E.P., 2018. Grassland fragmentation and its influence on woody plant cover in the southern Great Plains, USA. Landsc. Ecol. 33 (10), 1785–1797.
Scott, S.L., Rohde, R.F., Hoffman, M.T., 2017. Repeat landscape photography, historical ecology and the wonder of digital archives in southern Africa. Afr. Res. Doc. (131), 35–47.
Shantz, H.L., Turner, B.L., 1958. Photographic Documentation of Vegetational Changes in Africa over a Third of a Century. Photographic documentation of vegetational changes in Africa over a third of a century.
Shekede, M.D., Murwira, A., Masocha, M., 2015. Wavelet-based detection of bush encroachment in a savanna using multi-temporal aerial photographs and satellite imagery. Int. J. Appl. Earth Obs. Geoinf. 35, 209–216.
Shekede, M.D., Murwira, A., Masocha, M., Gwitira, I., 2018. Spatial distribution of Vachellia karroo in Zimbabwean savannas (southern Africa) under a changing climate. Ecol. Res. 33 (6), 1181–1191.
Shezi, T.A., O'Connor, T.G., Witkowski, E.T.F., 2021. Impact of livestock grazing intensity on plant diversity of montane grassland in the northern Drakensberg, South Africa. Afr. J. Range Forage Sci. 38 (1), 67–79.
Shoko, C., Mutanga, O., 2017a. Examining the strength of the newly-launched Sentinel 2 MSI sensor in detecting and discriminating subtle differences between C3 and C4 grass species. ISPRS J. Photogrammetry Remote Sens. 129, 32–40.
Shoko, C., Mutanga, O., Dube, T., 2019. Remotely sensed C3 and C4 grass species aboveground biomass variability in response to seasonal climate and topography. Afr. J. Ecol. 57 (4), 477–489.
Sibanda, M., Mutanga, O., Rouget, M., 2016. Discriminating rangeland management practices using simulated hyspIRI, landsat 8 OLI, sentinel 2 MSI, and VENμs spectral data. IEEE J. Sel. Top. Appl. Earth Obs. Rem. Sens. 9 (9), 3957–3969.
Skowno, A.L., Thompson, M.W., Hiestermann, J., Ripley, B., West, A.G., Bond, W.J., 2017. Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers. Global Change Biol. 23 (6), 2358–2369.
Smet, M., Ward, D., 2005. A comparison of the effects of different rangeland management systems on plant species composition, diversity and vegetation structure in a semi-arid savanna. Afr. J. Range Forage Sci. 22 (1), 59–71.
Stafford, W., Birch, C., Etter, H., Blanchard, R., Mudavanhu, S., Angelstam, P., Blignaut, J., Ferreira, L., Marais, C., 2017. The economics of landscape restoration: Benefits of controlling bush encroachment and invasive plant species in South Africa and Namibia. Ecosyst. Serv. 27, 193–202.
Symeonakis, E., Higginbottom, T., 2014. Bush encroachment monitoring using multi-temporal Landsat data and random forests. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. 40 (2), 29.
Symeonakis, E., Petroulaki, K., Higginbottom, T., 2016. Landsat-based woody vegetation cover monitoring in southern African savannahs. Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. 41, 563–567.
Tastad, A., Salkin, K., Battikha, N., Jasra, A.W., Louhaichi, M., 2010. Ecological dynamics of protected and unprotected rangelands in three climatic zones of Syria. Pak. J. Agri. Sci 47 (2), 89–98.
Thackway, R., Lesslie, R., 2006. Reporting vegetation condition using the Vegetation Assets, States and Transitions (VAST) framework. Ecol. Manag. Restor. 7, S53–S62.
Thondhlana, G., Muchapondwa, E., 2014. Dependence on environmental resources and implications for household welfare: evidence from the Kalahari drylands, South Africa. Ecol. Econ. 108, 59–67.
Trollope, W.S.W., 1980. Controlling bush encroachment with fire in the savanna areas of South Africa. In: Proceedings of the Annual Congresses of the Grassland Society of southern Africa, 15, pp. 173–177, 1.
Tsalyuk, M., Kelly, M., Getz, W.M., 2017. Improving the prediction of African savanna vegetation variables using time series of MODIS products. ISPRS J. Photogrammetry Remote Sens. 131, 77–91.
Venter, Z.S., Cramer, M.D., Hawkins, H.J., 2018. Drivers of woody plant encroachment over Africa. Nat. Commun. 9 (1), 1–7.
Vogel, M., Strohbach, M., 2009. July. Monitoring of savanna degradation in Namibia using Landsat TM/ETM+ data. In: 2009 IEEE International Geoscience and Remote Sensing Symposium, 3. IEEE, pp. III–931.
Ward, D., 2005. Do we understand the causes of bush encroachment in African savannas? Afr. J. Range Forage Sci. 22 (2), 101–105.
Ward, D., Hoffman, M.T., Collocott, S.J., 2014. A century of woody plant encroachment in the dry Kimberley savanna of South Africa. Afr. J. Range Forage Sci. 31 (2), 107–121.
Wasiolka, B., Blaum, N., 2011. Comparing biodiversity between protected savanna and adjacent non-protected farmland in the southern Kalahari. J. Arid Environ. 75 (9), 836–841.
Wigley, B.J., Bond, W.J., Hoffman, M.T., 2009. Bush encroachment under three contrasting land-use practices in a mesic South African savanna. Afr. J. Ecol. 47, 62–70.
Worku, B., 2018. Effect of post bush clearing management practice on herbaceous species productivity and soil status of rangelands in Hammer district of South Omo zone. J. Agric. Sci. Food Res. 9 (229), 2.
Yang, X., Crews, K.A., 2020. The role of precipitation and woody cover deficit in juniper encroachment in Texas savanna. J. Arid Environ. 180, 104196.
Dougill, A. and Trodd, N., 1999. Monitoring and modelling open savannas using multisource information: analyses of Kalahari studies. Global Ecol. Biogeogr., 8(3-4), pp.211-221.