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Land Change Science: Understanding the complexity of monitoring protected areas in savanna ecosystems of Sub-Saharan Africa[1]

Arazi Değişim Bilimi: Sahra Altı Afrika'daki savan ekosistemlerinde korunan alanları uzaktan algılama ile gözlemlemenin zorluklarını anlamak[2]

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ABSTRACT / ÖZ

Land Change Science (LCS), as a coupled human-environment system, is a multidisciplinary area that explores the dynamics of land use and land cover to understand key theories, problems, methodologies, and model applications. The present review integrated the research that have been conducted in the savanna ecosystem of Sub-Saharan Africa from a geographical perspective. The present study elaborates contemporary issues and thoughts in terms of several key aspects: (1) Impacts of protected areas on the surrounding natural environment, wildlife, and socio-economic activities of humans, (2) with the impact of new developments in remote sensing (RS) technology, observations of land change and the changes in the relationship between ecology and RS, (3) the effects of developments in RS on our environmental perspective and new connection opportunities for interrelated scientific disciplines, (4) the vulnerability of the savanna vegetation due to its multilayered and complex structure. Due to the changing climatic conditions, it is inevitable that ecosystems will encounter various problems in the near future, especially in Sub-Saharan Africa. Understanding the complex savanna ecosystem remains a challenge for researchers. Therefore, it is very essential to observe better and understand the nature and socio-economic cycle of human for a sustainable future of savanna ecosystems.

Bütünleşik bir insan-çevre sistemi olarak Arazi Değişim Bilimi (ADB), temel teorileri, sorunları, metodolojileri ve model uygulamaları anlamak için arazi kullanımı ve arazi örtüsünün dinamiklerini araştıran multidisipliner bir bilim dalıdır. Derleme şeklindeki bu çalışma Sahra Altı Afrika'daki savan ekosistemi bölgelerinde bugüne kadar yapılmış olan çalışmaları bir araya getirerek coğrafi bir perspektif çerçevesinde incelemektedir. Yapılan çalışmada; (1) Sahra Altı Afrika'da, korunan alanların, bu alanların sınırlarındaki insan yaşamı ve onların sosyo-ekonomik faaliyetlerin yanı sıra doğal çevre ve vahşi yaşam üzerinde önemli ölçüde etkiye sahip olduğunun anlaşılmaktadır. (2) ADB alanında uzaktan algılama (UZAL) teknolojisindeki yeni gelişmeler, arazi değişimi gözlemlerinin yanı sıra ekoloji ve UZAL arasındaki ilişkiyi de etkilemektedir. (3) UZAL teknolojisi ekolojik perspektif bilgimizi geliştirdiği gibi aynı zamanda birbiriyle ilişkili teknolojisi ekolojik perspektif bilgimizi geliştirdiği gibi aynı zamanda birbiriyle ilişkili bilimsel disiplinlerle bağlantı kurmak için yeni fırsatlar da yaratmıştır. (4) Savan bitki örtüsü, katmanlı ve karmaşık yapısı nedeniyle diğer birçok ekosistemden çok daha kırılgandır. Bu nedenle, değişen iklim koşulları ve çevresel değişimler nedeniyle özellikle Sahra Altı Afrika'da ekosistemlerin yakın gelecekte çeşitli sorunlarla karşılaşması kaçınılmazdır. ADB'deki yeni gelişmelere rağmen bu karmaşık ekosistemi anlamak araştırmacılar için bir zorluk teşkil etmeye devam etmektedir. Dolayısıyla savan ekosistemlerinde sürdürülebilir bir gelecek için doğal yaşam ve sosyo-ekonomik döngüyü daha iyi gözlemlemek ve anlamak oldukça önemlidir.

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1. Introduction

The hydrosphere, geosphere, biosphere, and atmosphere are changing from their natural states in the traditional sense because of increased human consumption needs (Goudie, 2008). One of the key questions from the past and present regarding the conflict of human-environmental systems is: "Do land use activities degrade the global environment in ways that ultimately harm ecosystem services, human well-being, and long-term sustainability?" (Turner et al., 2007). As an integrated human-environment system, LCS has emerged as an area that studies the "dynamics of land use and land cover (LULC) to understand fundamental theories, problems, methodologies, and model applications" (Takada et al., 2010). According to Turner and colleagues (2007) "LCS" is a primary element of global environmental research for sustainable land use. The four fundamental objects of LCS are (1) monitoring the continuing land change on the surface of the earth, (2) considering the LULC changes as part of the human-environment systems, (3) modeling the spatiotemporal changes of land, and (4) the implications of policy and management outcomes for resilience, vulnerability, and sustainability of the land use (Rindfuss et al., 2004; Hirota et al., 2011).

LCS is a recently developing field of science that aims to understand the causes, shapes, rates, and consequences of changing lands (Ozdes, 2023a). As a research area focused on exploring human and environment interaction using geographic information systems (GIS), LCS utilizes remote sensing data and tools specially to comprehend the dynamics of LULC as a factor of human-environment system (Baker, 1989; Özdeş et al., 2019). The focus area of LCS can be defined as theoretical, conceptual, modeling and applications related to environmental and social issues using pragmatic approaches (Figure 1).

A well-established scientific assessment on land changes requires human-environment interaction and cause-effect relationship from a geographical perspective, as well as monitoring and recording the changes of land surface over a long-time period (Rindfuss et al., 2004). Billie Lee Turner II. as an American geographer and human-environmental scientist is widely recognized as the pioneering geographer who introduced the term "Land Change Science" in scientific literature (Turner, 2002). Therefore, it would be appropriate to acknowledge Turner as one of the key figures in the development of Land Change Science, often referred to as its founding father (Figure 2). Turner and colleagues (2007) point to the followings as the most crucial contemporary research questions in the LCS field: (1) What changes are occurring in the terrain and what are their spatiotemporal applications? (2) What are the effects of such changes on the land for the environment and people, and how can the two be linked? (3) How can we integrate the perception of human-environmental system into a theory of land change systems and what are their implications? (Turner and Robbins, 2008; Lambin et al., 2001).

In LULC studies, particularly in studies involving time series analysis, remote sensing technology and the existing observational capability from airborne and space-based sensors, have a promising future. Nevertheless, it is essential to acknowledge that despite the progress made, several limitations in the field have yet to be addressed (Southworth & Muir, 2021; Southworth et al., 2016). As a result, substantial ongoing efforts are being devoted to further advancements in this domain.

Agricultural land is unquestionably one of the research areas where remote sensing and GIS techniques are most common-

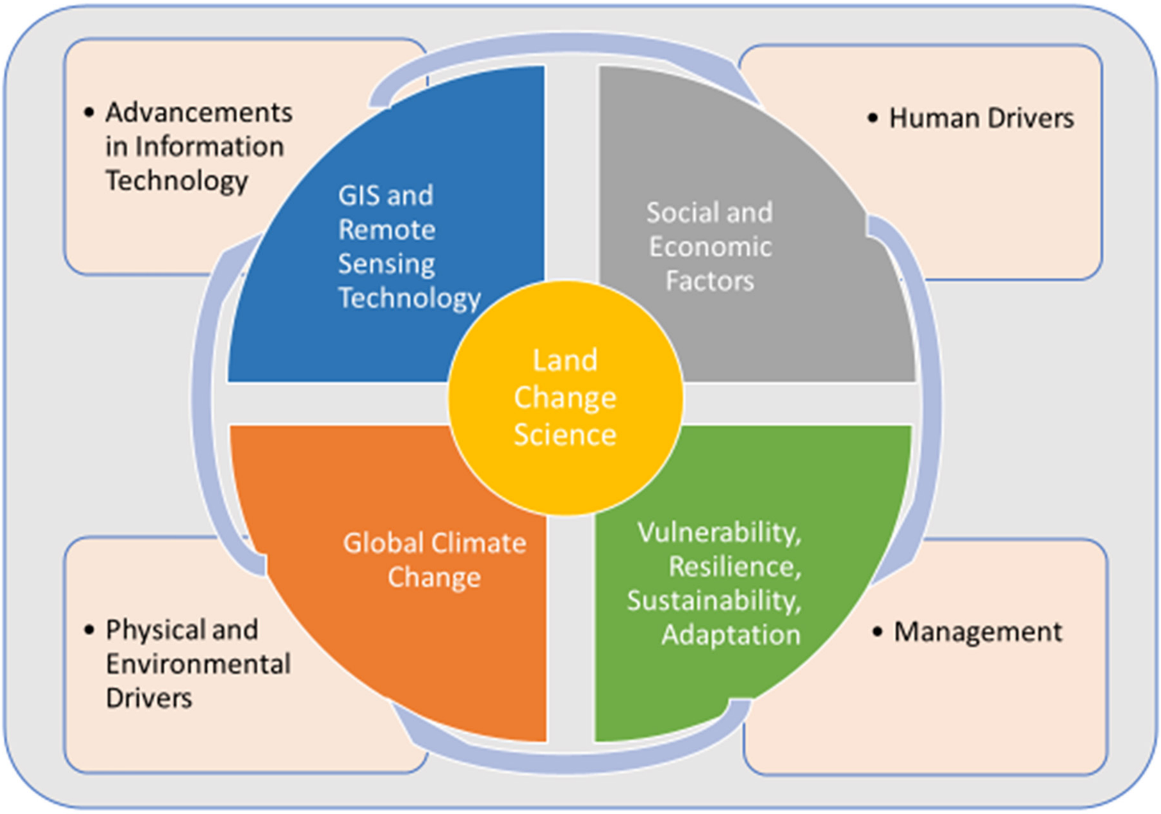

Figure 1. Conceptual model of Land Change Science surrounding by environmental and socio-economic factors.

ly used (Ozsahin et al., 2022a). The physical characteristics of agricultural lands determine the productivity and thus the capacity to meet human needs (Ozsahin & Ozdes, 2022a). Proper land use is one of the most important factors in achieving optimum agricultural productivity while ensuring the sustainability of ecosystems as well (Ozsahin et al., 2022c). Sustainable use of land resources is required due to geographic patterns of biophysical limits, the possibility for growing crops on specific types of land, and future implications of climate change (Özşahin et al., 2019; Ozsahin & Ozdes, 2022b). Therefore, the evaluation of land suitability in agricultural land should be considered as one of the most important applications of remote sensing and GIS.

Land change science faces challenges in integrating data, methods, and analyses due to technological and socio-cultural differences. Scaling issues arise when considering the dynamic interplay of time, space and human factors. Standardizing the scale or resolution used in data analysis is critical for consistency and reliability (Rindfuss et al., 2004). Dynamic factors in scaling include changes in land parcels, property rights, leasing, and zoning. Furthermore, land use complexity arises from the diverse utilization of the same land over time, as well as the concurrent occurrence of multiple uses (Brown et al., 2000). Mismatched boundaries between remote sensing data and land parcels are also a challenge. Excluding inaccessible or data-poor areas can lead to biased results (Rounsevell et al., 2012). Although high-resolution satellite imagery is helpful in detecting land cover classes, it has limitations in terms of interpretation errors, incompleteness, and obsolescence. Remotely sensed data allow for pixel-based inspection and classification, allowing for remote land measurements. However, the parcel-pixel relationship is uncertain in local socio-cultural studies and poses even more challenges (Brown et al., 2000). On the other hand, there is limited research in land change science to determine the most effective methods to overcome these challenges.

The sustainable management of savanna ecosystems is essential for the well-being of both humans and the environment. However, savanna ecosystems are under threat from a variety of factors, including climate change, land degradation, and overexploitation of lands. Further research, monitoring, and protection of savanna ecosystems is urgently needed to ensure their long-term sustainability.

The present review aims to detail the main principles guiding new concepts of likely drivers of LULC change in savanna systems in Sub-Saharan Africa and help respond to important questions in the LCS field in regard to remote sensing research. It is well known that land cover in savanna ecosystems is vulnerable to changes (van Wilgen & Biggs, 2011). Previous studies have shown that land cover compositions in savanna ecosystems have changed drastically in recent decades due to changes in protected area management policies, climate change, and other anthropogenic factors (van't Veen et al., 2021; Ozsahin et al., 2022b; Ozdes, 2023a). Additionally, the decision-makers, impact of tourism, changes in the population of large carnivores, fire policies, and co-management policies of settlers may mirror issues in numerous savanna locations in the Sub-Saharan Africa (Southworth & Muir, 2021). To improve adaptive management and the sustainability of protected areas, it is essential to understand the relationship between LULC and environmental parameters in savanna ecosystems (van Wilgen et al., 2008; Armitage et al., 2009). Therefore, the present review could potentially provide guidance for further research in savanna ecosystems.

The present review provides a comprehensive overview of the current state of knowledge and research on savanna land change from Sub-Saharan Africa and other regions and perspectives. The review is organized into the following sections: (1) Introduction, (2) current state of land change science research in African savanna ecosystems, (3) savanna ecosystems (4) shrub encroachment in savanna ecosystems (5) remote sensing of savannas (6) parks and protected areas in sub-saharan Africa (7) land change in and around protected areas (8) conclusions, implications, and future directions of land change science in savanna ecosystems.

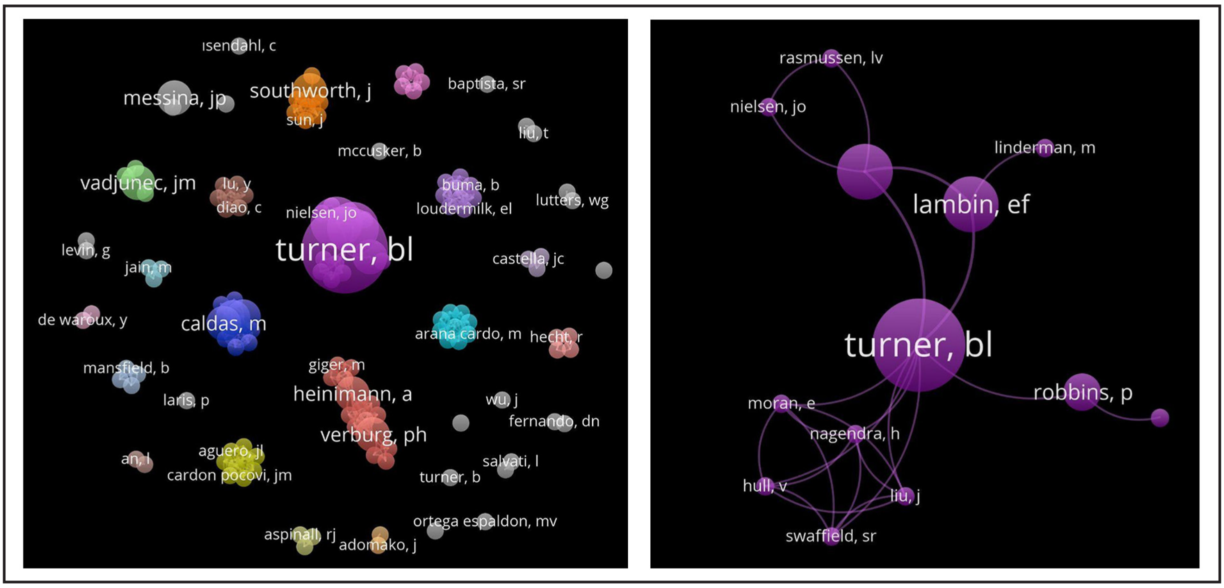

Figure 2. *The Concept of Land Change Science (left), proposed by Turner and his colleagues in his network (right), is visually represented using the Land Change Science terminology from the Web of Science literature. The image was created with WOSViewer.*

2. Savanna Ecosystems

A savanna ecosystem is defined as an ecosystem characterized by the presence of grasses and sparsely distributed trees, in which diverse communities of organisms interact to form a complex and interconnected food web. Typically, two main land cover types that considered as savanna systems are grassland and the tree cover (Sankaran et al., 2005). However, most researchers divide woody cover up to three subcategories, such as shrubs, brush, and trees (Venter, 1992; Wessels et al., 2011; Kiker et al., 2014). On the other hand, savanna ecosystems are naturally unstable combinations, rather than a balanced combination of trees and grasslands, because of disturbances such as grazing, fire, and fluctuations in precipitation over time (Scholes & Walker, 1993).

The savanna ecosystem, while recognized for its resilience, exhibits a higher susceptibility to changes compared to other ecosystems due to the intricate complexity and structure of its vegetation (Campo-Bescós et al., 2013). Consequently, the layers of vegetation frequently undergo replacement. However, the vulnerability of savanna vegetation is intimately intertwined with climate, herbivores, and wildfires. Any modifications within these components of the biome can lead to significant alterations in the entire vegetation structure. Thus, considering the vulnerability of Sub-Saharan Africa's savannas to climate change, it is plausible to anticipate potential environmental impacts in the region's future (Biggs, 2003; Bucini et al., 2010; Wessels et al., 2011; Bunting et al., 2016).

Significant emphasis has been placed on investigating anthropogenic-induced modifications in global land use patterns in recent decades. Particularly over the past thirty years, there has been a substantial focus on interdisciplinary and international research examining the impacts of human activities on land cover changes (DeFries et al., 2010; Wittemyer et al., 2008). However, comprehensively studying the intricate savanna ecosystem and the associated land cover transformations continues to pose challenges for scientists, extending beyond the limitations of remotely sensed data and data availability. This challenge is expected to persist in the future (Southworth et al., 2004).

Tree cover has a significant impact on the proper functioning of savanna ecosystems. These impacts can be found in different areas, including negative effects on productivity, evaporation rates, hydrology, nutrient cycles, and soil erosion. (Sankaran, et al., 2008). Research has been focused on computing the interactions between savanna structure and the environmental variables to identify their sensitivity to climate change related LULC. The relationship between the woody components and grassland in savanna biomes is of particular interest (Bucini et al., 2009). Previous studies have shown a strong positive dependency of plant growth on mean annual precipitation (MAP) between 200 and 700 mm per year (Gibbes et al., 2014). The threshold for MAP reliance was found to be insignificant when the effects of other observed predictors, such as fire, grazing, and logging, are considered (Sankaran et al., 2005). Studies in Sub-Saharan African savannas have explored the impact of key environmental factors on vegetation growth along physiographic gradients, including their role and magnitude (Campo-Bescós et al., 2013; Hoell et al., 2015). These studies commonly utilize the Normalized Difference Vegetation Index (NDVI) as a measure of vegetation greenness because it has been established as a dependable biomass index in most savanna ecosystems (Wessels et al., 2006). However, due to variances in land use decisions and management practices, the dynamics of these components exhibit significant variability in savanna regions and are unpredictable in most cases (Fullman & Child, 2013; Fullman et al., 2017). Therefore, it is unclear what promotes tree-grass coexistence and exactly what criteria influence the relative proportions of the two forms of flora in different savanna regions (Bond, 2008; Bardgett, et al., 2021).

For decision-makers, it is essential to comprehend regional variations in natural processes and the effect of land use management on savanna structure. That is, managing landscapes and knowing how savanna biomes will be impacted by future changes in climate and anthropogenic land use depend on understanding the mechanisms that are causing changes in savanna vegetation structure and function. Studies have previously discussed the significance and potential vulnerability of savanna ecosystems in global carbon cycles. Bucini and Hanna (2007) indicated that controlled fire is essential for maintaining the equilibrium of grasslands-tree cover and for the long-term carbon equilibrium. The magnitude of studying this particular subject will be more acknowledged given that the African savanna ecosystem contributes significantly to atmospheric CO2 emissions, largely through burning savannas (Sankaran et al., 2008; Smit & Asner, 2012).

In Sub-Sharan Africa, the savanna is a vital habitat for both human life and wildlife. It is essential to both the production and security of food around the world. Around 40% of the world's population resides in arid and semiarid regions, the majority of which are covered in savanna ecosystems (Sankaran et al., 2008; Cui et al., 2013). Savanna ecosystem is heavily utilized for agricultural activities in addition to its environmental and economic importance for natural habitat and wildlife. Recently, human pressure has increased through logging, grazing, and agricultural activities. Uncontrolled wildfires have increasingly affected the distribution and type of land cover and the loss of trees (Soulard et al., 2016). In some areas, increasing human pressure and decreasing rainfall have led to degradation of plant cover, and even desertification, loss of plant cover and shrub encroachment (Jacquin et al., 2010). Therefore, it is essential for policy makers and land managers to quantitatively evaluate the LULC of savanna change to help policymakers more effectively manage these key systems that are currently experiencing significant change.

3. Current State of Land Change Science Research in African Savanna Ecosystems

In sub-Saharan Africa, the savanna ecosystem provides a vital habitat for both human and wildlife. The production of food on a worldwide scale and the security of food supply for both people and the local wildlife depend heavily on these semi-arid regions of the planet. Over 40% of the world's population lives in regions with savanna vegetation and other dry or semi-arid climates (Sankaran et al., 2008). These areas have economic value for both governments and individuals, but they also have a variety of wildlife and natural habitat. On the other hand, recent human influences, such as overgrazing, agricultural operations, uncontrolled wildfires, and the manufacturing of charcoal, have, nevertheless, gradually altered how the land cover is distributed. This change is known as "woody cover loss". Furthermore, it has led to a disruption in the endemic vegetation cover and an invasion of shrubs in the African savannas (Jacquin et al., 2010). To better understand the trajectory of land change and its effects, it is crucial for land managers, policy makers, and governments to accurately quantify the LULC changes in savanna ecosystems.

Protected areas in savanna ecosystems have various challenges. Research in Sub-Saharan Africa has shown that forest area has decreased significantly since the beginning of the 21st century, but under current conditions, it is highly likely that it will continue to decline over the next few decades (Potapov et al., 2022). It is hypothesized that one of the primary reasons for this decline is linked to the increase in elephant populations in some protected areas that previous researchers have showed (Fullman and Child, 2013). Fullman and Child (2013) indicated that although presence of elephants attracts more visitors, they have also become a major administration problem in some key protected areas such as the Kruger National Park (KNP) in recent years. However, in contrast to the KNP, forest areas have increased in the Limpopo National Park (LNP), which is located in Mozambique and adjacent to the KNP. The fact that this park is a relatively new compared to KNP, may also have affected the difference between the two. Likewise, the vegetation of Kafue National Park (KANP), which is located in Zambia, has been well preserved inside the park. However, the expanding human population in the area surrounding KANP has turned into a major issue for both the park's administration and the Zambian government. As a result of rising human population and activities such as agriculture and settlement, a large amount of forest loss has taken place surrounding the park. It is most likely that these activities place extra stress on the flora and fauna of the protected areas. In general, it is crucial to consider the "whole picture" while planning such significant wildlife sanctuaries, considering both the protected area itself and the activities that take place around them. Otherwise, it would not be unexpected if protected areas turned into isolated eco-islands in the near future.

Studies in southern Africa have addressed the rates of deforestation caused by clearing for agricultural land and charcoal production (Geist, 1999; ZAWA, 2010; van't Veen et al., 2021). Increased improper land use is another crucial issue harming wildlife and livelihoods in savanna environments. (DeFries et al., 2007, 2010; Watson et al., 2015; Wittemyer et al., 2008). However, there is a need for an integrated approach to human-environment interactions, such as national parks and their buffer zones for specific livelihoods in the savanna regions of Africa, to address the 'edge effect' of these interactions around protected areas. Edge effects can significantly impact on the natural ecosystem of livelihoods (DeFries et al., 2007; Hansen and DeFries, 2007; Joppa et al., 2009; DeFries et al., 2010; Mondal & Southworth, 2010).

The effective dimension of the ecosystem and the ecological flows play a significant role in savannah regions. Changes in LULC around livelihoods may overlook potential unique habitats and have an irreversible effect on the source-sink subtleties of ecological environments (Hansen & DeFries, 2007). The administration of livelihoods focuses on ecosystem resilience and maintenance by using adaptive management techniques that support social and environmental interactions while encouraging the heterogeneity of vegetation cover and biodiversity (Olsson et al, 2007; Cheong et al., 2012). Therefore, it is important to explore the edge effects around protected areas and to better recognize the long-time consequences of LULC change. This is particularly important in regions where human settlements are the dominant driving force behind LULC changes. Most livelihoods in African savanna biome experience edge effects, but each livelihood experiences them differently, depends on several factors. For example, KNP is being destroyed by large herbivores such as elephants (Fullman and Child, 2013). KANP and LNP, on the other hand, seem to be lacking sufficient number of large animals. Thus, while forest area is generally decreasing in KNP, it is increasing in KANP and LNP. Additionally, shrub encroachment is a continuing problem in KNP, but a decreasing trend of shrubs is observed in KANP. LNP, on the other hand, does not show a decreasing trend, but the level of shrub is seen to be stable.

Research utilizing LCS has indicated that savanna ecosystems are subject to encroachment by human activities. Nevertheless, accurately quantifying the magnitude of this encroachment is often misrepresented due to various factors, including cloud cover in satellite imagery, areas affected by fire, and improper application of remote sensing techniques. Complex savanna landscapes are difficult to adequately describe using conventional classification algorithms. Additionally, savanna landscapes have frequently been incorrectly classified in large-scale studies (Hansen et al., 2013; Friedl et al., 2014), underestimating the level of human encroachment (Vinya et al., 2011), or under considered in governmental reports (ZAWA, 2010). However, recent advancements in research have employed machine-learning algorithms to classify the primary land covers within savanna ecosystem regions using medium- to high-resolution satellite data collected over extended time periods. These approaches have demonstrated improved accuracy in detecting land changes in Sub-Saharan Africa. To highlight the human impact within these vital savanna landscapes, the emergence of modern GIS technologies and remote sensing has enabled us to differentiate between natural areas and anthropogenic land use.

4. Shrub Encroachment in Savanna Ecosystems

In savanna ecosystems, the shrub encroachment has been observed to be a continual process. Increases in density, cover, and biomass of shrubs are referred to as "shrub encroachment" (Van Auken, 2009). The phrase "shrub encroachment" is synonym with a variety of other broad terms including "woody thickening," "bush encroachment," and "shrub invasion" (Eldridge et al., 2011). Walker and colleagues in the savanna biomes (Walker et al., 1981; Walker & Noy-Meir, 1982; & Westoby et al., 1989) later developed the idea after it was first introduced by Walter (1954).

Out of all areas of research in savanna lands one of the most well-researched occurrences is the shrub encroachment on savanna landscapes. The primary causes of shrub encroachment can be linked to both anthropogenic and natural activities (Maestre & Cortina, 2005). However, in most cases the shrub encroachment is linked to human disturbances including overgrazing, fire, and other anthropogenic activities (Archer et al., 1995; Sankaran & Anderson, 2009). Shrub encroachment is a widespread experience in most of the arid and semi-arid regions of the world (Eldridge et al., 2011). Due to the combined effect of grazing and tree cutting, these types of changes in vegetation formation have increased since the beginning of the 20th century (Archer, 2009; Pacala et al., 2001; Knapp et al., 2008). Recent changes in the dynamics of the vegetation in sub-Saharan Africa are being caused by the increased dominance of shrub-like plants over grass and tall tree cover (Blaser et al., 2014). Shrub encroachment threatens 13 million hectares in sub-Saharan Africa, and the loss of savannah systems is thought to have an impact on more than two billion people globally (Adeel, 2008; Archer, 2009).

Multiple plants, including several Acacia species, are linked to be invasive in the savannah environments of southern Africa: twisted Acacia *(Vachellia tortilis)*, blue thorn *(Senegalia erubescens)*, blackthorn *(Senegalia mellifera)*, brendi bush *(Grewia flava)*, sicklebush *(Dichrostachys cinerea)*, silver terminalia *(Terminalia sericea)* and mopane *(Colophospermum mopane)* are some of them (Moleele et al., 2002). In sub-Saharan Africa, the presence of an upper limit on woody vegetation, along with increases in MAP, implies that shrub invasion is largely relies on the presence of water (Sankaran et al., 2005). In such case, even if all other factors remain unchanged, changes in rainfall could be more effective in increasing the process of shrub encroachment than grazing.

5. Advancements in Remote Sensing of Technology

Remote sensing has developed rapidly in the last 40 years in parallel with the development of space technology, computer, and information systems. Approximately four decades ago, the prospect of accurately mapping the extent of global forest coverage was a mere aspiration. However, today we possess the capability to collect and analyze comprehensive data on global forest gain and loss on a monthly basis. It is worth noting that the research and methodologies in this field are still in their nascent stages, necessitating substantial advancements and progress (Hansen et al., 2013). Remote sensing and GIS have made significant progress in recent years in a variety of technological fields, from methods to sensors. This has led to notable improvements in environmental and ecological monitoring (Hill et al., 2016). It has also enhanced the connectivity between geography, environmental science, ecology, and other related disciplines (Southworth & Gibbes, 2010) Additionally, the availability of free high-resolution and medium-resolution satellite images has made it possible to map and observe regions with a greater range of analysis than small-scale landscapes (Cho et al., 2012). Accessing the ecosystem information via remotely sensed data not only improved our observation abilities, but also created new opportunities for the social and environmental research areas.

Although there are many limitations yet, remote sensing is a promising technology in terms of the observation capability of ground, air, and space sensors (Southworth & Muir, 2021). Therefore, it should be acknowledged that to strengthen the connections between remote sensing, LCS, studies of the economic and social fabric of human advancement should be taken into account in addition to ecological field investigations (Chambers et al., 2007; Pontius et al., 2004). As a result, over the past 40 years, remote sensing technology has advanced quickly, enabling precise and thorough mapping of the world's forests. Advancements in remote sensing technology has greatly enhanced our understanding of the environmental perspective and has generated new prospects for interdisciplinary research.

6. Parks and Protected Areas in Sub-Saharan Africa

KNP is among the most varied protected areas in the Sub-Saharan savanna regions in terms of flora and fauna. The park is located in the Lowveld region of the South African Republic but have borders with Mozambique in the east and Zimbabwe in the north. As a result, the area around the park's boundary is has a wide variety of economic policies and land use management strategies. Thus, there are various differences in terms of ecosystems, social structures, and cultural elements. Any substantial change in the LULC significantly impacts the social elements and natural environment of the local community, which is dependent on the natural resources, agricultural revenue, and tourists (Munyati & Ratshibvumo, 2010; Shikolokolo, 2010). Therefore, there are numerous reasons to consider and research the LULC change, including the expansion of the surrounding communities and the sustainability of the natural ecosystem.

Recently, studies have been conducted using current satellite images on different subjects. For example, a termite suitability study was recently carried out in KNP to better understand the relationship between plant cover distribution and termite habitat (Ozsahin et al., 2022b). Using a ten-year land cover change trajectory within the KNP, a long-term land cover change was previously carried out and provided a better understanding of plant cover change (Trollope et al., 1998). Another study that examined the spatio-temporal variation of the woodland, barren/built, burnt, grassland, shrubland, and water classes in both the KNP and surrounding landscape mosaic from 1989 to 2013 for a period of 24 years (Ozdes, 2017). This research was conducted on LULC change using Landsat images at different time points (Figure 3). The study also applied a combination of Cellular Automata and Markov Model to predict the spatio-temporal trajectory of the land cover change by focusing on the boundary between the Greater Limpopo Transboundary Park (GLTP) in Mozambique and the KNP and LNP. The main idea of assessing the land in a comprehensive perspective in this area is based on the opinion that the success rate is higher for an internationally large-scale protected area rather than focusing on smaller protected areas within a single country (Hansen & DeFries, 2007; GLTFCA, 2016). In other studies, Cellular Automata and Markov Models are combined to forecast the spatiotemporal course of future land cover change (Hsu et al., 2008; Kamusoko et al., 2009; Mondal & Southworth, 2010; Kumar et al., 2014; Hyandye & Martz, 2017). As a result, the studies confirm that contrasting the changes in land cover inside and outside the protected areas help understanding the factors causing land cover change.

According to Büscher (2010), the transboundary element has the potential to greatly improve the benefits that protected areas now offer to local populations. Conservationists are prompted to work on a bigger scale by transboundary protected area operations. Crossing political boundaries is important since these boundaries generally do not reflect natural systems and do not prioritize the protection of the overall ecosystems. Protected areas that have been combined under the GLTP concept into one sizable transboundary conservation area include the Gonarezhou National Park, Gonarezhou regions, the area between Kruger and Gonarezhou, the LNP, the KNP, the Malapati Safari Park, the Manjinji Pan Conservation Area, and the Makuleke region in Sub-Saharan Africa with a total area of about 100,000 km^2 (Lunstrum, 2010). This concept promises to have a positive influence on social, political, and ecological improvements. These changes range from the anticipated displacement of a few thousand people who already reside within the boundaries to numerous and wide-ranging improvements, such as the removal of any fences along international political borders and the restocking of some wild species. A prediction of LULC change will also aid in a better understanding of how local population relocation, which began in 1998, and these changes may or may not have an impact on vegetation cover change. Therefore, this project may be a way to rationalize and justify a rich transboundary park in terms of both wildlife and tourism opportunities.

7. Land Change in and Around Protected Areas

Among the various types of governance and management, one of the most classical ways to protect landscapes and maintain its sustainability is through the development and expansion of national parks and protected areas. As a general research statement, LULC changes in the surrounding area of protected areas have a major effect on protected areas themselves (Child et al., 2004; DeFries et al., 2007). In the last three decades, protection of landscapes as protected areas has gained particular attention regarding the land dynamics and nature of the protected areas boundaries as well as the surrounding landscapes. Beside human existence and social activities surrounding the protected areas, natural environment and wildlife significantly bounded to the protected areas. In addition, the human presence around protected areas has a direct impact on the natural cycle of protected areas (Simasiku et al., 2008; Richardson et al., 2012). Therefore, research shows that the connection of protected areas with their environment is important; such that higher connectivity levels can help decrease possible habitat loss and balance the equilibrium in protected areas and the surrounding landscape (Shikolokolo, 2010; Lindsey et al., 2014).

The burden on protected areas is increased by human-dominated activities such as population expansion, agriculture, grazing, and other associated activities. The majority of these activities have the potential to directly impact both protected areas and their surroundings. Often simultaneous changes in plant type and structure come from changes in land use, such as those brought on by shrub encroachment (Sankaran, et al., 2008). The main causes of shrub encroachment are typically the disappearance of large trees and pastures because of increasing grazing, fires, and increase in shrub cover that is not very advantageous for wildlife. Although ongoing changes in land use continue to affect many parts of the world, they are particularly high in Sub-Saharan Africa. Studies conducted in the last three decades predict that this change will continue to affect protected areas and that these changes will cause more shrub encroachment (Venter et al., 2008). One of the major wildlife locations in sub-Saharan Africa, Kruger National Park (KNP), has seen a significant increase in shrub infestation over the past three decades (Dowsett, 1966; Eckhardt et al., 2000). Beyond wildlife problems in both protected areas and adjacent lands, activities in and around protected areas with high human populations have a critical role in the overall health of the PA ecosystem. (Hansen and DeFries, 2007).

KANP is located in the northern section of the typical savanna ecosystem in Zambia, and the buffer zone surrounding it, represents another important protected area in Sub-Saharan Africa (Ozdes, 2017). Surrounded by nine game management areas (GMAs) makes the importance or the area even greater in terms of socio-economic activities as well as environmental factors (Petit et al., 2001; Midlane, 2013; Rduch, 2016). The environment and vegetation cover in KANP were affected to different degrees during the 1964 Zambian independence war (Child, 2009). The Zambia Wildlife Authority (ZAWA) now permits locals to dwell in GMAs as part of its policy (ZAWA, 2010).

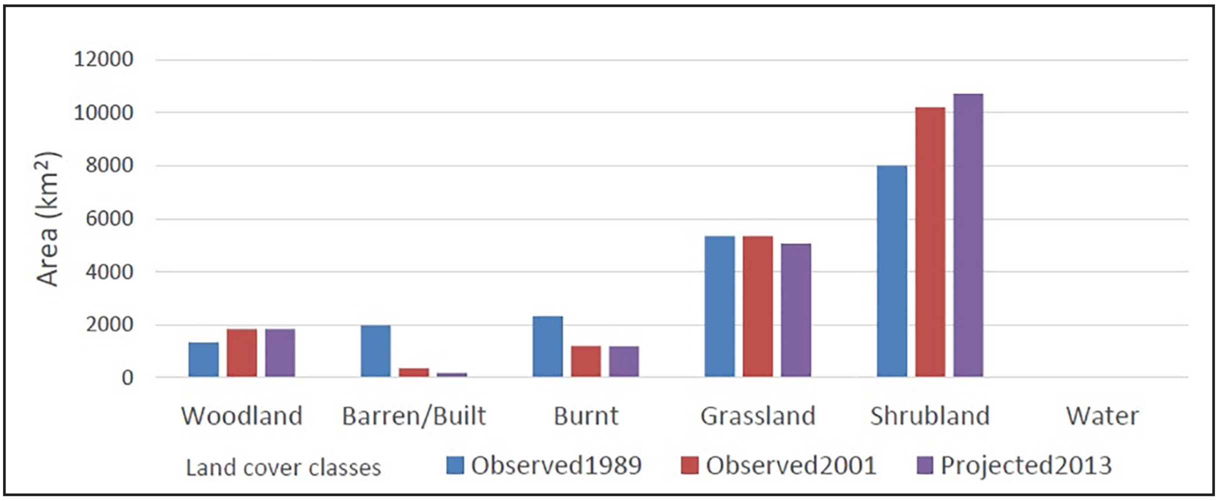

Figure 3. *Land cover and land use change within Kruger National Park have been examined by analyzing Landsat images captured at multiple time points over a comprehensive period of 24 years (derived from Ozdes, 2017).*

Recent study, however, raises the possibility that these settlements could endanger the flora and fauna of the protected area (Ozdes, 2017). As the largest and oldest national park in Zambia, KANP has an area of about 22,400 km2 (Ellenbroek, 2012). In addition, it is regarded as one of Sub-Saharan Africa's parks with the most biologically diversified flora and animals Within the park's boundaries, there have historically been human settlements and agricultural operations, but today these regions are off limits (Mwima, 2001). On the other hand, there has been a significant change in land cover around KANP in the last three decades (Figure 4). These changes are primarily due to rapid increase of the local population, which resulted in increased agricultural activities in the GMAs surrounding the park, as well as illegal activities such as settlements, poaching, and burning. Therefore, comparing land cover changes and additional GMAs in KANP has allowed for a better interpretation of recent changes.

KANP is one of the natural areas that have not been affected by excessive anthropogenic impairment in the ecosystem. Despite the presence of a considerable amount of wildlife in the park, the exact number of the fauna is still unknown. Additionally, there are several areas that need to be researched, including those involving soil structure, geological formations, and biological variety in addition to vegetation cover and habitat alterations (Mwima, 2001).

Recent studies have associated the LULC changes in KANP and its surroundings with settlement and agricultural changes that have occurred in this region in the last three decades (Ozdes, 2023b). Studies are continuing to classify LULC more accurately in the area comprising of KANP and surrounding GMAs. A more detailed representation of the LULC is possible by combining field data randomly collected for vegetation cover type and structural classes with satellite remote sensing data, vegetation indices, and land cover classifiers like Random Forest. (Breiman, 2001; Prasad et al., 2006; Cutler et al., 2007; Strobl, 2010; Rodriguez-Galiano et al., 2012). Additionally, improvements in LULC change trajectory have made it easier to comprehend how the vegetation has changed over the past thirty years.

8. Conclusions, Implications, and Future Directions of Land Change Science in Savanna Ecosystems

The savanna ecosystem is known for its diversity and the support it provides for large animals and human populations. However, despite its ecological importance, it has been overlooked in terms of understanding its role in global environmental change and socioeconomics. Advancements in earth observation systems have not been effectively utilized in studying savanna systems, specifically in identifying main structural and operational attributes. The use of high-resolution and medium-resolution data to identify land-use and land-cover changes in savanna ecosystems presents significant challenges and limitations. Traditional remote sensing methods struggle to accurately identify the composition of trees, grass, and shrubs in the landscape. These limitations include a lack of

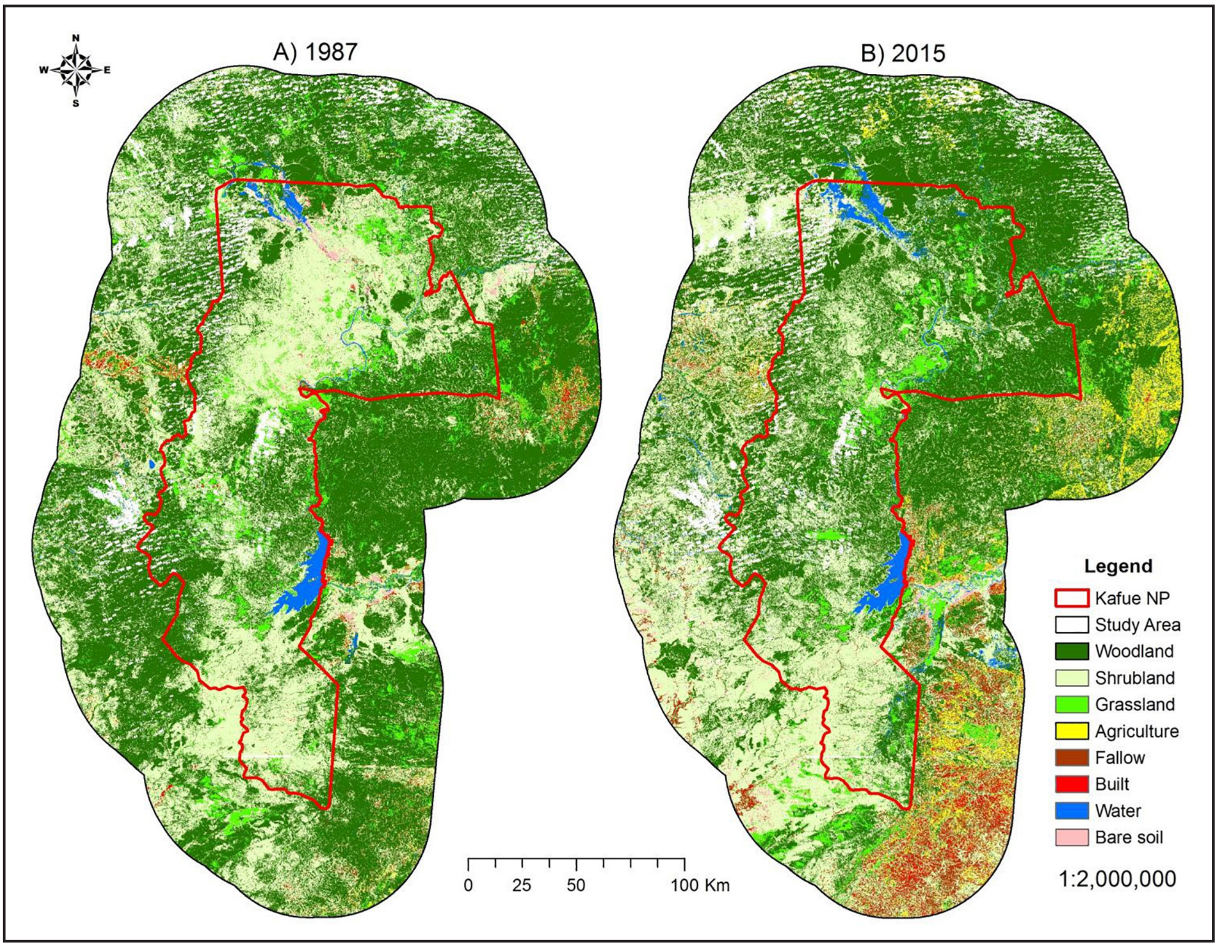

Figure 4. *Land cover changes in and around Kafue National Park in the past three decades primarily result from population growth, increased agricultural activities in surrounding GMAs, and illicit practices like settlements, poaching, and burning (derived from Ozdes, 2017).*

frequent imagery, cloud cover, errors in remote sensing data, and the need for extensive fieldwork to verify data.

Fortunately, new satellites orbiting in space (for example, Landsat 8 and 9, Sentinel-2) continuously collect low, medium, and high-resolution data around the world, and many of them are freely available for scientific research. In addition, more advanced methodologies such as machine learning and artificial intelligence (AI) enable better land classification studies in much larger areas (Ozdes, 2023b). In addition, research is currently directed towards forecasting potential modifications in the land cover of savanna ecosystems in the future. Assessing and predicting changes in LULC in sub-Saharan Africa is crucial in setting goals and determining the success of these transboundary regions, rather than focusing solely on smaller protected areas within individual countries. Additionally, using current data and prediction techniques to model the future landscapes of protected areas will identify potential challenges across these areas and provide insight into changes in neighboring regions.

LCS has become increasingly important in understanding the dynamics of savanna systems, particularly in remote sensing applications. Recent advancements in remote sensing technologies have enabled researchers to monitor land cover changes at large spatial scales and high temporal resolution. These improvements have led to increased accuracy when mapping landscapes over time for various purposes such as monitoring climate change, land degradation, and vegetation health.

The remote sensing technologies used in LCS are now being utilized to better understand the ecology of savanna systems, particularly those in sub-Saharan Africa. Researchers have been able to identify specific species-specific responses to climate change, land use changes, and seasonal variability. By monitoring the changes over time, it is possible to develop a better understanding of how savanna ecosystems respond to environmental change.

In addition, remote sensing data collected by LCS can be used to inform policy decisions that can help protect savanna systems from further degradation. By monitoring land cover changes over time, policymakers can make informed decisions about land-use planning and management strategies. This information can also be used to inform conservation efforts and identify areas of high ecological value that need protection.

The future of LCS in savanna systems is optimistic, as remote sensing technologies continue to improve and researchers can develop a better understanding of the dynamics of these ecosystems. As remote sensing technology advances so too will the ability to monitor changes in land cover over time and make informed decisions about conservation efforts. Moreover, remote sensing data can be used to develop predictive models that help anticipate future changes in savanna systems due to climate change or land use changes. This could be used to inform policy makers of potential management strategies and identify areas of high ecological value before they are degraded.

The remote sensing data collected by LCS will not only help inform policy decisions but also provide a valuable resource for scientists looking to better understand savanna ecosystems. With remote sensing technology continuing to improve and new applications being explored, remote sensing has the potential to help protect savanna ecosystems from further degradation and ensure their long-term sustainability. The future research questions surrounding protected area management and sustainability using remote sensing technologies of savanna systems in sub-Saharan Africa are as follows:

1. How can remote sensing data be used to inform policy decisions for land use and conservation in savanna ecosystems?

2. How can remote sensing data be used to monitor land cover changes over time and develop predictive models of future changes in savanna systems?

3. How effective are remote sensing technologies at identifying areas of high ecological value that need protection?

4. What new remote sensing applications and techniques can be used to improve the accuracy and precision of remote sensing data in savanna ecosystems?

5. How can remote sensing technologies be used to help local communities and stakeholders better understand, monitor, and manage land use in savanna ecosystems?

6. What are the ethical implications of using remote sensing technologies for protected area management and sustainability in savanna systems?

7. How can remote sensing technology help bridge the gap between research and policy decisions in savanna ecosystems?

8. What new remote sensing technologies are being developed to better monitor savanna systems and inform conservation efforts?

By exploring these questions, researchers can gain a greater understanding of remote sensing technologies, their application in savanna systems, and their potential to help protect these ecosystems from further degradation.

Overall, LCS has the potential to be a powerful tool in monitoring, predicting, and managing savanna systems. The future of remote sensing technologies in these ecosystems is bright and can be used to help protect them from further degradation. With this information, policymakers can make informed decisions that benefit both the environment and local communities. If applied correctly, LCS has the potential to be one of the most valuable tools in savanna conservation.

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