THE IMPACTS OF ANTHROPOGENIC FIRES IN WEST AFRICAN SAVANNA WOODLANDS AND PARKLANDS: THE CASE OF THE GUINEA SAVANNA, GHANA

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A thesis submitted in fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY (Environmental Science) at Rhodes University, South Africa.

DECLARATION

I, **Esther Ekua Amfoa Amoako**, hereby declare that this thesis is my own original work which is being submitted to the Faculty of Science, Rhodes University, South Africa for the degree of Doctor of Philosophy (PhD). It has not been submitted before, either in part or in full for any degree or examination in any other University. References of other researchers used in this thesis have been duly acknowledged.

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ABSTRACT

Fire is recognised as an important factor influencing the structure and function of tropical savannas. Despite the extensive studies conducted on the effects of fire on global savannas, there are relatively few studies focusing on fire-assisted land use practices in the agroforestry parkland of the Sudano-Guinean savannas of West Africa. The region experiences recurrent fires in the dry season which begins from November to April. The fires are anthropogenic and are mainly caused through rural livelihoods and cultural practices such as farming - to remove debris from crop fields and to improve soil fertility and hunting to flush out animals, among other reasons. This study therefore sought to: 1. contribute to the understanding of fire-assisted traditional land use practices, people's knowledge and perceptions of fire use and fire regime: 2. analyse the effects of fire on vegetation, and 3. determine the effects of fire on soils in the Guinea savanna woodlands and parklands of Ghana. Study sites (burnt and unburnt land use types) were selected based on five-year daily fire counts (2013-2017) data, obtained from the Earth Observation Research and Innovation Centre (EORIC), Ghana in collaboration with the Council for Scientific and Industrial Research (CSIR) Meraka Institute, South Africa. Fire densities were calculated for the 18 districts in the Guinea savanna (Northern Region of Ghana). The districts were stratified into low, medium and high fire frequency areas. The East Gonja district recorded the highest fire density (1.0 fires km^{-2}) while Tamale recorded the lowest fire density (0.3 fires km^{-2}). Of the eighteen districts, six districts were purposively selected and ten communities sampled. Firstly, I investigated the frequency of fire use and control, perceptions of fire regime for selected livelihood and socio-cultural activities in the six districts. The majority of respondents (83%) across the study districts indicated that they used fire once a year for at least one of the following activities: land preparation, weed/grass/pest control, burning stubble after harvest, bush clearing around homesteads, firebreaks, charcoal burning and hunting. The study showed the highest frequency of fire use in the dry season was for land preparation for cropping. However, less than a fifth of the respondents (17%) indicated that they did not use fire for any of the above activities. The results of a multiple regression predicted fire activities in the dry season from gender, age, level of education, occupation and household size. Secondly, the study examined how fire influenced the population structure and abundance of two economically important woody species *Vitellaria paradoxa* C. F. Gaertn. (Shea tree) and *Anogeissus leiocarpa* (DC.) Guill. & Perr. (African Birch) in burnt and unburnt land-use types. Stand basal area, mean densities of juveniles and adult trees and Simpson's index of dominance were determined. Eight diameter size classes of each species were analysed by comparing their observed distributions to a three-parameter Weibull distribution across the

land use types. A total of 3,366 individuals of *A. leiocarpa* (n = 1,846) and *V. paradoxa* (n = 1,520) were enumerated. The highest total basal area of *Anogeissus leiocarpa* (16.9 m^2/ha) was estimated in sacred groves whereas *Vitellaria. paradoxa* (20.6 m^2 /ha) was found in unburnt woodland. The highest mean densities of *A. leiocarpa* (22.7±29.7 stems/ha) and *V. paradoxa* (15.3±2.2 stems/ha) were found in sacred in groves. *Anogeissus leiocarpa* was, however, absent in fallows and burnt crop fields. A somewhat inverse J-shaped distribution was found in sacred groves for both species. Thirdly, the study compared species composition in early burnt, late burnt and unburnt plots in a protected area where fire was regulated. *Vitellaria paradoxa* C. F. Gaertn., *Terminalia avicennioides* Guill. & Perr., *Combretum adenogonium* Steud. ex A. Rich. and *Combretum molle* R. Br. Ex. G. Don. were the most common and abundant in all treatments. Late burnt and unburnt plots recorded the lowest diversity amongst the three treatments. Unburnt plots had higher tree density than burnt plots. A Detrended Canonical Analysis showed a changing trend, indicating a moderately strong positive association between burning time and species composition. The first and second axes contributed 53% and 12% variation, respectively. Most of the species found in axis one had fairly strong positive association to early and late burnt treatment than unburnt treatments. Finally, the effects of fire on soil properties in burnt and unburnt crop fields and woodland in the ten communities were also investigated. A total of 151 composite samples in selected burnt and unburnt land use types (burnt crop field n=20; unburnt crop field n=27; burnt woodland n=53, unburnt woodland n=51) were analysed. The variables analysed were pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorous (P), Exchangeable bases - potassium (K), magnesium (Mg), calcium (Ca), cation exchange and soil texture. Total N, SOC, pH and Ca differed significantly across the burnt and unburnt land-use types. A principal component analysis showed a stronger association and more positive gradient in woodlands than in crop fields. Total N showed a positive association with SOC, whereas silt showed a negative association to sand and clay. Traditional knowledge and perceptions of users of savanna agroforestry parklands can inform the formulation of local by-laws for community fire management as well as national policy regulation on fire use in the savanna through the interlinked analysis of social and ecological systems as have been elucidated in this study. The results on vegetation assessment revealed that fire practices and land uses influenced size class distribution of the two study species as well as the densities of woody species in traditional crop fields and the National Park. The unstable populations observed in most land uses and the absence of *A. leiocarpa* in crop fields and fallows call for education and policy actions on the use of fire in parklands of West Africa. Furthermore, fires positively influenced some soil properties in both woodlands and crop fields confirming one of the emphasised reasons why rural subsistence farmers use fire. As an environmental management decision and land use policy intervention, early dry season burning could be an option to curbing the indiscriminate and unplanned fire use. Also, the protection of trees on farm lands could check the unstable population structure of economically important woody species leading to the different structures that deviated from the recommended reverse J-shaped distribution curve observed in these agroforestry parklands. The management of socio-ecological systems such as the agroforestry parklands of West Africa require a holistic understanding of the complexity of the different resource systems, units and actors involved for sustainable management of these natural resources.

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CHAPTER 1: GENERAL INTRODUCTION

Background

Fire is recognised as one of the most significant agents in savanna ecology (van Wilgen 2009; Osborne et al. 2018). It is estimated that the total annual area burnt globally is between 4.2 and 4.7 million km^2 (Benali et al. 2017). Forty-four percent of global burns occur in grassland and savannas and 15% in woodlands. It is also acknowledged that fires in African savannas contributed about 70% of global burnt area and about half of global fire carbon emissions (van Der Werf et al. 2010; Morton et al. 2010; Giglio et al. 2018).

Like other terrestrial ecosystems, savannas provide regulating, provisioning, cultural and supporting ecosystem services to the people who live therein and beyond. Woody species in savannas provide edible fruits, medicine, wood for fuel and construction, as well as timber and non-timber forest products for local use, and in some instances for export and income (Nyingi et al. 2018; Sinare et al. 2016). The herbaceous layer provides fodder for livestock and wild game, and thatch for housing for both humans and livestock as well as medicine. Significantly, the herbaceous layer serves as the primary source of fuel for fires in savannas around the world (Huffman 2013; Bond and Zaloumis 2016).

Approximately 90% of fires in Africa are caused by humans (Knowles et al. 2016; Dwomoh and Kimberly 2017). The use of fire for socio-cultural and livelihood activities has modified savannas either directly or indirectly (Laris 2011) and positively or negatively depending on the scale (Treuarnicht 2015). Thus, a prominent characteristic of African savannas is that most of the vegetation is regularly disturbed and fragmented, spanning a range of forms, from open broad-leaved woodland to wooded grassland, bush fallows and parklands (Chidumayo and Gumbo 2010).

Nyingi et al. (2018) reported that the indiscriminate use of fire in land preparation for cropping, hunting, poaching and pasture management contributes to the loss of biodiversity in African savannas. The conversion of savannas into agricultural or pastoral land and in the pursuit of other traditional livelihood activities, is often accompanied by burning of biomass, which is recognised as a major driver of change in African savannas (Dwomoh and Wimberly 2017). Hence, fire impacts have both temporal and spatial implications at the local and global level (Dwomoh and Wimberly 2017). Table 1. Summarizes reasons for fire use, spatial and temporal scales and the areas of impacts.

Table 1. Some reasons for fire use, spatial and temporal scales and the areas of impact. Early, mid or late season depends on the climate and location

Reason for fire use	Ideal burn season	Spatial scale of burn	Temporal scale of burn	Area of impact
Increase visibility/improve movement	early-mid season	local	annual	livelihoods
Prevent damaging wildfires	early-mid season	regional	sub-annual	livelihoods
Protect cropland and houses	early-season	local	annual	livelihoods
Prepare croplands	end of season	local	annual	livelihoods
Attract grazers/modify grazer movements	varied	local	sub-annual	livelihoods/conservation
Alter tree-grass dynamics: reduce tree cover	late season/summer	local regional	decadal	livelihoods/conservation
Increase biodiversity	varied	regional	decades to millenia	livelihoods/conservation
Alter tree-grass dynamics: increase tree cover	early season	local/ regional	decades to millenia	conservation

Early, mid or late season depends on the climate and location
Source: Adapted from Archibald and Amoako, Pau Costa Virtual Conference Presentation, October 2020.

Several studies (e.g. Bond and Keeley 2005; Osborne et al. 2018) have indicated fire as a major determinant of savanna vegetation structure, composition, richness and dynamics, signifying that fires can either enhance or be detrimental to savannas, depending on the fire regime and land use (Govender et al. 1996; Keeley 2009). The management of African savannas is therefore greatly influenced by fire-assisted land use systems which revolve around traditional crop and animal husbandry (Ockwell and Lovett 2005; Coughlan 2014) and other livelihood activities (Table 1), and to a lesser extent, formal conservation of legally protected sites (CILSS 2016). The degree to which land use and management affect savanna resources, whether traditional or conventional, is vital in the functioning of African savannas (Chidumayo and Gumbo 2010; Osborne et al. 2018). In some contexts, however, fire disturbances can exceed the regenerative capacity of the savannas which may be exacerbated by the current conditions and threats from climate change in Africa (Stevens-Rumann and Morgan 2016).

Despite the recognition of extensive use of fire in savannas of Africa, traditional fire use with associated land use and other socio-cultural practices such as using fire for firebreaks, clearing travel routes and hunting, and their impacts on the environment remain poorly described and under-researched (Laris and Wardell 2006; Eriksen 2007; Huffman 2013). Although these practices are at a small scale, their cumulative impacts on savanna woodlands, parklands, bush fallows and croplands significantly contribute to global ecology (Sinare and Gordon 2015). Bush fallow is an agricultural land use practice common to West and Central Africa, where a small plot cultivated for 3-5years is then left for much longer periods usually greater than five years, to restore soil fertility. In contrast, the croplands are characterised by scattered mature trees. Most agricultural and other livelihood activities occur in the parklands (area of scattered trees with a herbaceous layer of grass and shrubs) referred to as agroforestry parklands (Boffa 1995; Schreckenberg 1996; FAO, 1997; Boffa 2000). Thus, knowledge on the effects of fire use from the various fire-assisted land use and livelihood practices is useful to determine the ecological impacts of fire, especially on savannas and agroforestry parklands.

Fires come in different sizes, types, intensities, seasons and frequencies depending on the purpose of use. The interactive impact of fire attributes such as type of fire, flame height and fire behaviour are understudied in traditional fire management but highly considered in fire experiments and protected sites (Eriksen 2007; Huffman 2013). However, Huffman (2013) mentioned in a review study on traditional fire uses across six continents that in traditional fire knowledge, people consider some environmental conditions such as weather and season which scored highest in literature available across the six continents (Huffman 2013). The same author, however, indicated that it was evident that some rural people who used fire had limited understanding on how some fire attributes interact and influence one another. The lack of the understanding could be attributed to the diminishing traditional fire knowledge (Huffman 2013). Just to mention a few, the study showed 32 out of 35 papers on traditional knowledge showed little understanding of season of burning and 22 of the 35 papers did not consider vegetation structure as important during burning, respectively. This has led to the failure of most fire management policies in most fire prone communities as community members disregard these fire attributes in their fire applications. The study further showed less research on vegetation type and attributes such as fire type (14), and as low as six studies for the rate of spread (Huffman 2013). However, in fire ecology, it is the interaction of all fire attributes that shapes vegetation and the impacts on soils as well as global climates. There is therefore the need for the integration of indigenous and scientific knowledge on fire for sustainable fire management at all levels and must be aligned with the local context as much as possible.

In Africa, most fires are for livelihood purposes. For instance, fire for land preparation for cropping made on small farms characterise the subsistence agriculture in Africa. Ramo et al. (2021) detected more small fires from croplands (less than a hectare - not easily detected by MODIS) than large fires from the woodlands in sub-Saharan Africa. However, fires at the landscape level contribute to bigger impacts at the global scale. This is confirmed by Ramo et al. (2021), that small fires from croplands, accounted for 41% of overall global burnt area per annum. Thus, the contribution of small fires is critical in sub-Saharan Africa and the estimates raise the contribution of biomass burning to global burdens of (greenhouse) gases and aerosols. Although, Ramo et al. (2021) did not address burning on all biophysical components of ecosystems, their study raises concern on the impact of small fires on global climates, vegetation and soils.

In West African savannas, for instance, fire use for agriculture is not only attributed to the type of slash and burn agriculture practiced in forest areas around the world, but, also burning open natural vegetation in savanna areas (Huffman 2013). Similar to Australia and other parts of the world, the fires are set to old farm lands to prepare the land for the cropping or woodlands to open up new areas for new farms (Laris 2011; Huffman 2013). The fires consume dead and dying grasses, tree litter, shrubs and small trees (Laris 2011). Laris (2011) and Huffman (2013) explain that these fires are set to achieve multiple livelihood purposes. To this extent, it is appreciated that fire practices in savannas influence species survival, abundance and diversity.

Despite the recognition that most fires in the African savanna are human-caused, several studies on savanna fire ecology rarely integrate fire and land use systems (Laris 2011). In this context, it is important to explore the impact of fire assisted land use practices on vegetation and soils that are of importance in ecosystem function as well the perceptions of the people on the use and control of fire (Eriksen 2007). This could inform fire management plans and policies that are founded on traditional ecological knowledge in terms of pointers from fire regimes, species survival, diversity and other ecological processes.

The ecology of the African savannas

Savannas cover 20% of the land surface of the earth, mainly in the tropics and subtropics, between arid regions and wet equatorial forests, in areas with dry winters and wet summers (Shorrocks and Bates 2015). They have been defined variously so much that it is difficult to use the word savanna in a precise sense. Ecologically, savannas are defined by their biotic characteristics, which include co-dominance of herbaceous vegetation interspersed with few or many trees and abiotic factors such as climate and topography (Hanan and Lehmann 2010). Typically, they are defined by the percentage contribution of woody and grass species, as well as climatic (e.g., rainfall and temperature) and edaphic factors (e.g., soils types and topography). Charles-Dominique et al. (2015), for instance describe savannas as a discontinuous tree cover with a continuous layer of C4 grasses. Olusegun et al. (2018) identified C3 grasses in the African savannas as playing a significant role despite their low abundance. Shorrocks and Bates (2015) classified savannas into tropical and subtropical types, adding a more diversified interplay of the characteristics of savannas in Africa. Tropical savannas are mainly found in Africa and Latin America (Charles-Dominique 2015). The types include the Sahel, Sudan, Guinea, Miombo and Mopane savannas found in Africa, the Cerrado in Brazil and Terai-Duar in Asia and Australia (Shorrocks and Bates 2015).

Greenway (1973) classified savannas in Africa into dry forests, woodlands, wooded grasslands, grasslands, bushlands and semi-desert vegetation depending mainly on the woody-grass ratio and height of trees (generally exceeding 100 cm). The combination of the biotic and abiotic factors such as topography, soils and climate, determine the structure of savannas (Gaillard et al. 2018). However, in the last 20 years, the interface of climate and fire has been a topic for discussion because it is predicted that changing climate is likely to alter fire occurrence and spread, particularly in the tropics, thus effecting vegetation structure and dynamics (Monmany et al. 2017). Thus, the ability of savannas to accommodate fire disturbances is critical for the sustainability of African savanna ecosystems (Sebata 2017).

Shorrocks and Bates (2015) indicated that tropical savannas are characterised as subclimax vegetation communities and are greatly influenced by anthropogenic fires (pyric subclimax), farming and grazing (biotic subclimax). Sebata et al. (2017) mentioned herbivory in addition to fire as important determinants of the structure and composition of the woody vegetation of some southern and eastern African savannas. West African savannas however, have lower wild ungulate population pressure, but a higher diversity of understory woody cover in response to fire and other disturbances (Du Toit and Cumming 1999). The diversity of plant and animal species in African savannas, therefore, differ from place to place and are significantly influenced by fire assisted land use practices and herbivory. Thus, fire is considered a major disturbance in West African savannas (Thonicke 2001).

The extent and types of African savannas

Savannas occupy 43% (about 13 million km^2) of the land area of Africa (Osborne et al. 2018). African savannas are described as tropical and subtropical vegetation types distinctively spreading between latitudes 15° North and 30° South and longitudes 15° West and 40° West (Duvall 2011). African savannas are characterised by open tree canopies or without trees at all and form two of the three main types of global savannas i.e., woodland and shrubland biomes

(Osborne et al. 2018). These savannas cover multiple countries in Africa, from Guinea to Nigeria in the west, through the Central African Republic to Tanzania and Malawi in the east, and extending from Zambia through Botswana to South Africa in the south (Chidumayo and Gumbo 2010).

Similar to other savannas, the categorisations of African savannas are based on the tree-grass ratio, structure of woody and herbaceous species, edaphic, topographic and climatic attributes (Spinage 2012). The exact ratio is a function of numerous variables, both natural and anthropogenic. Invariably, West African savannas are categorised into three broad climatic zones – sub-humid, warm mesic and warm dry – each forming a relatively narrow band to form the Guinean forest-savanna mosaic, Sudanian savanna and Sahelian Acacia savanna, respectively (Chidumayo and Gumbo 2010; CILSS 2016).

Furthermore, Keay (1959) classified West African savannas as the warm mesic dry woodlands and sub-humid dry forests, into the Sudan and Guinea savannas, respectively. These savannas are hot and dry for most of the year, corresponding to up to eight months in the Sahel regions (CILSS 2016). The rainy season in the savannas of Africa is mostly unimodal and may occur from May to October and November to February depending on the location. Thus, most savannas receive from 250 up to 1,300 mm of rain a year depending on the location (Shorrocks and Bates 2015).

The Sudanian savanna merges in the north latitude zone with the *Vachellia* and *Senegalia* savannas, occurring in the Sahel which receives 300-650 mm annual rainfall and lies between sub-deserts to the north with rainfall as low as 100-300 mm per annum. The Guinean forest-savanna receives 1,200-1,500 mm annual rainfall and is a highly varied habitat dividing the rainforest from the Sudanian savanna. North of this Guinean-forest is embedded the Guinea savanna woodland which receives 900-1,200 mm annually (CILSS 2016). The Sudanian savanna (650-900 mm annual rainfall) occurs in the north of the Guinean woodland, which extends to some parts of Central and East Africa, where it is known as the East Sudanian savanna, through to the eastern Zambezian savannas and other southern African countries (Spinage 2012).

In the Guinean and Sudanian savannas, Chidumayo and Gumbo (2010) found that the majority of the areas are dominated by annual species of herbs and grasses due to the short rainy season. Factors such as long periods of drought, rainfall variability and large-scale burning of biomass to convert these savannas into agricultural and pastoral lands, and human settlements pose a threat to soils, plants and animal species.

The Zambezian savanna includes the Miombo and Mopane forms (Shorrocks and Bates 2015). The Miombo is characterised by high species diversity (Frost 1996; Gumbo et al. 2018). According to Ribeiro et al. (2020) Miombo woodlands cover 1.9 million km^2 in seven countries of south-central Africa. These miombo landscapes are varied, as are the ecological factors. For instance, the annual precipitation in southern Zimbabwe ranges from 600 mm to over 1,600 mm in southern DRC, whilst mean annual temperature ranges from 19 °C in central Angola and Zimbabwe to 25 °C in northern Mozambique. Not so different from the other savannas, the ecology of the woodlands is driven by climate, soils and disturbances. Given the extent of woodland cover change, the variability in structure and composition across the region is enormous and not always directly related to the determinants. Also, Frost (1996) and Ribeiro et al. (2020) reported that Miombo woodland is maintained by frequent fires and exploitation by people and wildlife. The authors recognise fire as a complex disturbance whose effect on Miombo woodlands varies according to the prevalent fire regime and land use history.

The continuous herbaceous layer of perennial grasses (prominently C4), sedges and sometimes shrubs is also a characteristic of the African savanna biome with distinct wet and dry seasons (O’Connor and Everson 1999; Faber-Langendoen et al. 2016). C4 grasses are very productive in the rainy season and highly flammable in the dry season (Bond and Zaloumis 2016). The Serengeti plains in East Africa, for instance, have a very dry grass savanna, with volcanic soils that have high nutrient content mostly classified as silty loam. Thus, there is probably no need to burn for soil fertility. Yet, in Zambia for instance, the Chitemene system of cropland preparation which involves the use of fire to increase soil fertility has been practiced for centuries (Eriksen and Gill 2010).

Soils in West Africa, on the other hand, are more of sandy loam and infertile (Chidumayo and Gumbo 2010). The moisture content of the soils is generally low due to their extensive weathering contributing to the low fertility of soils (Shorrocks and Bates 2015). The low moisture in the soils results in minimal downward chemical transportation and the low accumulation of salts and carbonate minerals (FAO 2000). Thus, the low nutrient level is the most claimed reason why farmers apply fire (Laris 2011) to the annual (e.g., *Pennisetum pedicellatum* Trin) and perennial grasses (e.g., *Heteropogon contortus* (Linn.) P Beauv) that dominate these savannas with the intention to improve soil nutrient levels from the ash and carbon from the burnt biomass (Laris 2011).

Aside from the high diversity of plant species and soil types, African savannas harbour the world's greatest diversity of ungulates (Du Toit and Cumming 1999). However, livestock now dominate the ungulate biomass of Africa which has enormous implications on how fire is used to manipulate savannas for livestock husbandry (Hempson et al. 2017). However, Hempson et al. (2017) argued that continuous use of fire destroy habitats for livestock.

Anthropogenic fires in African savannas

Africa is branded as the fire continent due to the widespread occurrence and frequencies of fire observed by satellites at different times of the year (Knowles et al. 2016). Natural fire ignition, such as by lightning or friction between dry leaves, is extremely rare (Laris 2011; Archibald 2012). It is important to point out that most human ignitions in Africa are not accidents. There are good reasons for the fires that people light, but they are just different reasons from what the international community sees as important when it comes to the use of fire (Sally Archibald, personal communication, 2020). Thus, the causes of fires in unprotected areas have been associated with traditional fire uses for diverse activities, including control of harmful flies, poaching, tapping of honey, hunting, land preparation for new cropping season, improve visibility and stimulation of fresh grass growth for animals (both domestic and wild) (Trollope 2011; Huffman 2013).

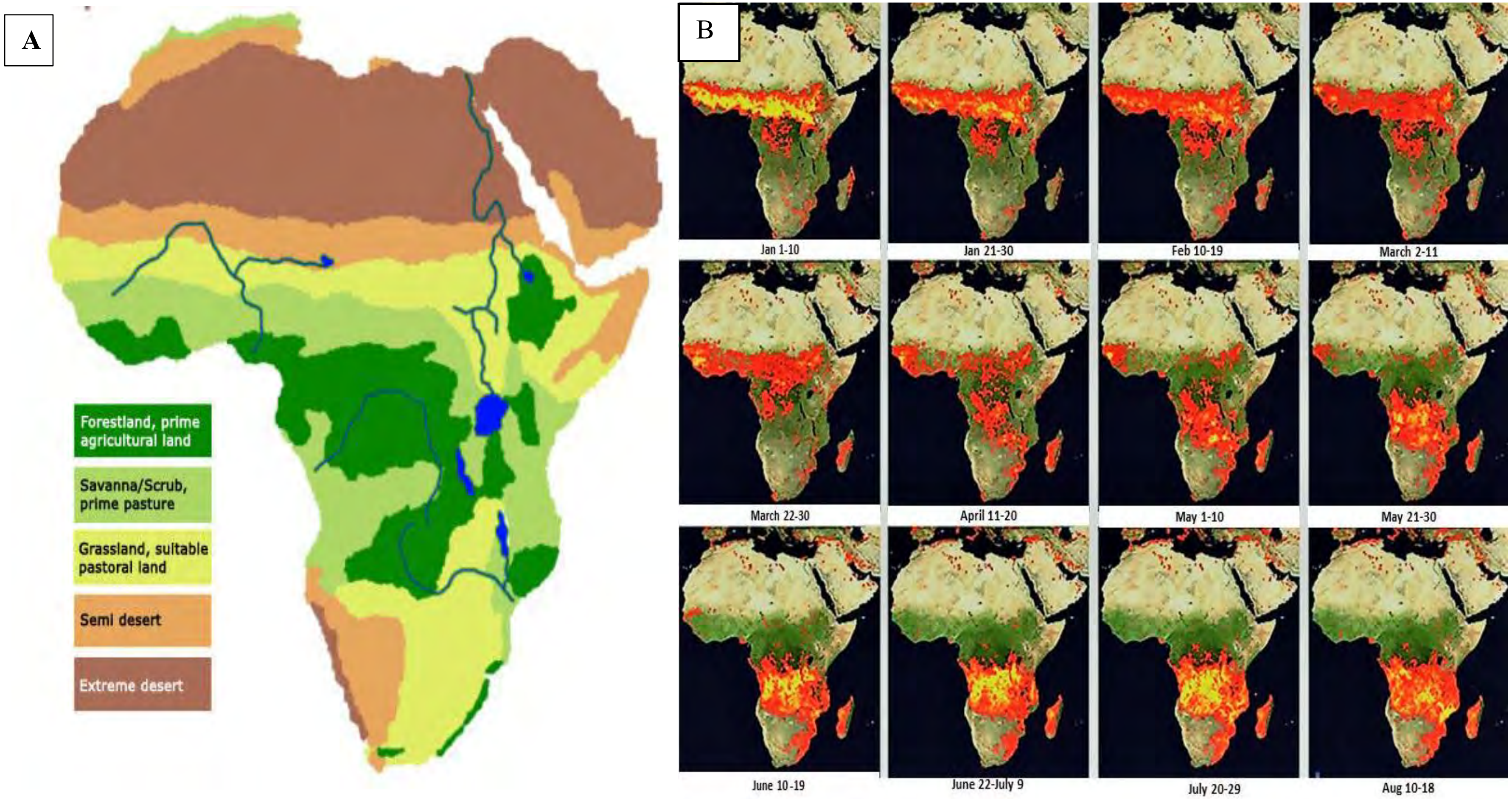
In African savannas, rural people basically burn when the dry grass fuels are available, it is very hard to prevent fire when there is sufficiently dry fuel load. Thus, it is more difficult to suppress fire than to practice controlled burning (Archibald 2016). While it is acknowledged that there is more fire use in unprotected sites than protected sites, most studies have been on the effect of fire on vegetation, soils and animals in protected areas than unprotected areas (Eriksen 2007). There is often a generalisation of effects of fire on the environment, with less consideration of the practical details of traditional uses of fire that differ from one place to another depending on local, social and environmental conditions. More often than not, studies on fire effects are conducted under controlled conditions than uncontrolled fire conditions, typical of unconfined commons and unprotected wildlands (Laris 2011; Huffman 2013).

There are a few studies on traditional fire uses. A few examples include Butz (2009), who investigated how Maasai tribes of East Africa use small fires at a landscape scale in savannas throughout the dry season to create a fragmented burn pattern and to prevent catastrophic late-season fires. In the Brazilian Cerrado, Eloy et al. (2019) studied how pastoralists create seasonal mosaic patterns of burnings performed to protect fire-sensitive vegetation and avoid wildfires. However, there are some knowledge gaps in the interactions between human-caused fires, land uses and fire regimes-e.g., fire type and spread (Huffman 2013) and how these affect population structure and abundance of woody species, soils and animals in unconfined areas or the commons.

The gap is largely because studies on fire effects on plants, soils and animals in experiments are thought to automatically clarify issues of traditional fire regimes and the different savanna landscapes. However, some studies acknowledge that traditional fire use is complex, as it varies even within the same landscape (e.g., Laris 2011; Huffman 2013). For instance, the effects of early burning in a protected area in the Guinea savanna may or not be the same as in an unprotected area in a different savanna or even in the same savanna. Therefore, the intricacies of the interaction of fire regimes, vegetation patterns, land use and human applications of traditional fire use in the different savannas of Africa need to be understood.

Some studies (e.g., Shaffer 2010; Archibald 2016) argue that most deliberately set fires are controlled. However, in West Africa, fires occurring during the Harmattan (north-east cold, dry, dust-laden wind with wide fluctuations in the ambient temperatures of the day and night) are difficult to control. The Harmattan season is characterised by extreme fire weather on a daily basis with low relative humidity (<15%), high air temperatures (37º C) and high wind speeds (20-50 km per hour) so that fires left unattended are usually destructive (Kugbe 2014). N'dri et al. (2018), however, found that some of these conditions, especially wind speed, did not affect fire behaviour in Lamto Reserve located in the Guinea savanna of Ivory Coast. The authors, however, attributed their observation to the low wind speed in the reserve at the time of the experiment.

The cycle of fire (Figure 1) runs through the savannas from November to March in the West Africa, August to September in the East Africa and November to December in Southern Africa (Knowles et al. 2016). Figure 1 shows the major types of savannas and the annual cycle and occurrence of fire across Africa.



Source: White andTimberlake

Source: NASA MODIS Active Fire product

Figure 1. **A** - Major types of landscapes including in Africa savanna **B** - The cycle of fire on the African continent, which peaks in January in West Africa and reaches Southern Africa in August. The olive-green shade represents all the savanna zones; the amber and orange mixtures are burning flames.

Ignorance and negligence have also been identified as contributing to uncontrolled bush burning in some parts of Africa (Shafer 2010; Archibald, 2016). However, there are cultural underpinnings and beliefs on traditional use of fire, which instils confidence in people to burn without considering the long-term implications or impacts of fire (Amanor 2002; Huffman 2013). Cultural festivals, such as the fire festival of some ethnic groups in the West Africa, and communal hunting (a well organised system in the north of Ghana known as 'Pieli'- comprising of 80 -100 persons who use fire to flush out animals by burning the dry grass) are vivid examples (Amanor 2002; Adongo et al. 2012). In the south of Ghana fire use for socio-cultural activities for different fire seasons have names that connotes the season and the activity of fire use (Pyne 2003).

Aside from the use of fire for cultural and traditional socio-economic activities, uncontrolled fires could be the result of arson (Shafer 2010; Archibald 2016). Shaffer (2010) indicated that children mimicking parents who use fire can cause fires as well. Thus, children who have grown up to become adult farmers in these traditional settings are likely to perpetuate traditional fire use. Knowledge of the fire use in farming systems is passed from generation to generation and thus embedded in the cultural dynamics of agro-pastoral economies of Africa (Bassett et al. 2003).

The reasons for the use of fire as shown above suggest that the traditional uses of fire in the African savanna are mainly for socio-cultural and livelihood gains, and less so for management of vegetation as practiced in conservation sites. Nonetheless, traditional fire use has both intended and unintended effects on the biophysical environment both at the local or landscape scale in the short and long term. Thus, fire applied in savanna woodlands, parklands and croplands for whatever purpose, has effects (either positive or negative) on the vegetation and soil. For instance, woody species such as *Vitellaria paradoxa*, which is one of the most economically important woody species in the Sudano-Guinean savanna, has adapted by developing thick bark to resist the annual hot fires (Hall et al. 1996). *Anogeissus leiocarpa*, on the other hand, is fire-sensitive and needs protection from fire.

Yet, the effects of the widespread use of fire in the types of savannas that predominate in West Africa - pyric subclimax (Aubréville 1949; Treurnicht et al. 2015) have received little research attention and understanding. This is with respect to linkages among fire use practices, fire regimes and vegetation dynamics as well as soil properties. In spite of the numerous livelihood benefits associated with traditional fire use, the continuous and indiscriminate burning of vegetation without regulation could hamper future development opportunities and livelihood options (Kugbe et al. 2012; Nyingi et al. 2018). Thus, it is important to examine the dynamics of fire use and effects of fire on the vegetation population structure of pyric subclimax savannas as one way to understand the value of small-scale fires and land use relationships on vegetation, soils and environmental management as a whole.

Effects of anthropogenic fires on savannas

Fires have many implications for biological diversity (FAO, 1999). Fire effects on savannas are dependent on the fire regime (size, type, frequency, season and intensity of fire). Fire intensity for instance, is influenced by the fuel load, fuel moisture content, speed and direction of the wind and weather (Gambiza et al. 2005; van Wilgen 2009). The interactive impact of fire attributes such as type of fire, flame height and fire behaviour, season of burn and frequency that are highly considered in fire experiments and protected sites, if well understood by traditional fire users can contribute to the sustainable management of savanna (Eriksen 2007; Huffman 2013).

Indeed, fires influences savanna soils and tree populations, and may alter ecosystem function at the landscape, regional and global level (Bassett et. al. 2003; Certini 2014; Knowles et al. 2016). Fire use for croplands preparation for instance, is normally done by the middle to the end of dry season and has an annual impact on soil potential at the local level. However, the visible effects of fire use for this same purpose (cropland preparation) on biodiversity may take a decade or more to have impact at the regional level.

Human-ignited fires are associated with drier, mostly less-forested landscapes, which could limit fire spread, hence could be controlled. In contrast, natural fires can be more devastating than anthropogenic fires (Griffiths et al. 2015). This is due is to the homogenous nature of natural fires. Implying that once fire occurs through lightening, for instance, the accumulated fuel burns more intensely and over large extents. Anthropogenic fires exhibit heterogenous patch mosaic burn characteristics and is believed to better promote diversity of plant communities than natural fires (Griffiths et al. 2015). Other studies (e.g., Sheuyange et al. 2005) have also shown that human-caused, high frequency fires have an ecological impact on tree, shrub and herbaceous plants. Sheuyange et al. (2005), however, found that the response of vegetation cover to fire regime and fire history was scale-independent.

Although fire has been shown to trigger germination of some savanna species (Duval 2016; Dayamba et al. 2010), it has been documented by Gray and Bond (2015) that fire effects are not only evident on vegetation but also soils and other savanna components. Gray and Bond (2015), however, found that soils respond to the changes in vegetation, instead of being the determinant of vegetation, suggesting that fire studies on plant communities at the plot or landscape level without considering the soil nutrient levels can omit important insights.

Fire effects on vegetation

Fires continue to be among the most important factors influencing the structure, composition and distribution of savanna communities. Fires affect the growth, regeneration and recruitment processes of many plant species (Bond and Midgley 2001). Thus, the effects of fire on the survival, diversity and abundance of plant species have been an important subject in savanna research and management. The fire regime, in addition to the extent and type of human interference, determines the species that comes to dominate specific plant communities (Bond and Midgley 2001; Ruthven 2003). Results obtained from a study on fire effects on vegetation in Nigeria, however, indicated both depressive and stimulatory effects depending on the type of species (Birnin-Yauri and Aliero 2010).

Frequent use of fire may eliminate less fire-tolerant woody and grass species, as found in Texas by Ruthven et al. (2003). This condition has been observed in the Guinea savanna of Ghana, which is gradually mimicking the Sudan savanna with reduced diversity and low tree and grass density (Blench 2001). Nonetheless, in some instances, anthropogenic fires are necessary for managing vegetation quality, through the elimination of competing plants and stimulation of growth of desirable plant species that improve habitats (Sheuyange et al. 2005). Some studies have shown that fires favour the growth of some plant species e.g., belonging to the Leguminosae, whereas other plant species become extinct in the long-term (Gill et al. 2005: Sheuyange et al. 2005; van Wilgen 2009). For instance, in Nigeria, Birnin-Yauri and Aliero (2010) showed a reduction in density and gradual disappearance of *Cyperus rotundus* and *Imperata cylindrica* after the second term of fire, whereas some herbaceous species showed a progressive increase in density during the period of burning. The unburnt plot in the experiment maintained all species with a gradual increase in density of almost all the species at the end of the experiment.

In the Booderee National Park, Australia, Fontaine et al. (2009) identified more vegetation types and increased associated bird diversity after 15 years of fire than sites that had not been burnt for decades prior to the wildfire. A greater understory cover and lower woody stem density in frequently burnt sites than rarely burnt sites was observed, indicating that fire can increase plant and animal communities in the long term. In south eastern Australia an experiment in a *Eucalyptus* Forest showed greater diameter at breast height (dbh) growth from 1996 to 2018 in an annually burnt treatment than a triennially burnt treatment (Lewis 2020). Higher tree growth rates in the annually burnt treatment could be due to the lower density of understorey woody plants in the treatment (Lewis 2020). In contrast, Foster et al. (2017) observed that sites that were long-unburnt prior to a wildfire had a higher understory cover compared to sites that were rarely burnt.

Other experiments in the Miombo woodlands of East and Southern Africa, however, showed that tree populations and trees with large stems are vulnerable to fire, with top-kill rates of up to 12% in intense fires (Ryan and William 2010). However, this rate is considered not damaging so that trees can resprout when exposed to favourable environmental conditions (Bond and Midgley 2001). Sapling top-kill ranged from 81% to 100% in burnt plots, in contrasted with 13% non-fire top-kill of saplings on the unburnt plot. This confirms the assertion that annual fires destroy nearly all smallest diameter stems, leaving a disjointed population within the juvenile classes and inconsistences between the medium and larger classes (Lykke 2008). It is also well known that not all juveniles survive before maturity even in undisturbed environments. As such the survival of juveniles is even worst in fire dominated environments (Lykke 2008).

N'dri et al. (2018) found that mid and late season fires did not have significant damaging effects on trees in the Guinea savanna contrary to what has been observed by Williams et al. (1998) in northern Australia and Savadogo et al. (2007) in Sudan savanna, Burkina Faso. The authors attributed this observation to most trees shedding their leaves after the early fires before mid and late dry season fires. Thus, living tree tissues of the trunk and branches are resistant to fires until the beginning of the rainy season when trees begin to have new leaves (N'Dri et al. 2018).

Amoako et al. (2018) identified a higher diversity of tree species in Guinea woodlands burnt in an early dry season, than in unburnt woodlands in the Guinea savanna, which suggests that some savanna species need fire for regeneration while others do not survive under fire. Nonetheless, all fires occur under different conditions, different fire regimes and exhibit varying fire effects and implications on vegetation. Thus, in fire prone areas such as the

Sudano-Guinean savanna, species that require no fire to germinate as found in the Mole National Park, Ghana would be affected negatively (Amoako et al. 2018). Fire-vegetation relation can be a good indicator for species abundance, exhibiting species responses to fire. Knowledge of species that that are tolerant, resistant or sensitive to fire can inform sustainable management of fires at the landscape level.

From the examples above, it is appreciated that most fire studies are usually conducted under regulated and monitored conditions. Trends in species survival are also continuously monitored to promoting the healthy plant communities especially in protected sites. This is, however, not the case in common pool landscapes such as found in most part of the African savanna and agroforestry parklands in particular. Studies on species survival in most traditionally managed savannas are normally based on the perceptions of the people rather than direct monitoring.

In an agroforestry parkland of Benin for instance, Hall et al. (1996) indicated that *Vitellaria* regeneration was increased when some selected areas of the parkland were protected from fire compared to the annually burning areas. The same authors indicated that the perception of the people was that, fire had significant effect on the first time of fruiting, as well as annual fruit production, in parkland trees such as *Vitellaria paradoxa* and *Parkia biglobosa*. Farmers in Niger have the perception that fires stimulate upward flow of sap which stimulates fruiting. Hence, they used fire to stimulate fruit production in *Vitellaria paradoxa* if it stops bearing fruits for 2-4 years (FAO 1997). The above-mentioned effects of fire use for cultural and livelihood practices, such as applying fire to stimulate fruiting in parklands could have unintended effects on population structure of the vegetation in parklands. However, there is little empirical study of fire assisted practices on population structure of woody species in these savannas and parklands.

Fire effects on soils

Fires can substantially alter nutrient cycling in burnt areas (Santin and Doerr 2016). Fire-soil processes, thus, have potential importance in global nutrient cycling (Kugbe et al 2012; Santin and Doerr 2016). Santin and Doerr (2016) mentioned that soils are among the most valuable non-renewable resources that are influenced by biomass burning.

Fires reduce above-ground litter cover that determines chemical properties and physical properties of soil (Knowles et al. 2016). Removal of vegetation cover during burning exposes the soil to erosion , reduction in soil porosity and bulk density (Keizer et al. 2008). Fire of

400ºC and above damage soil organic matter, resulting in a reduction in cation exchange capacity (Nsiah-Gyabaah 1996; Gonzalez-Perez et al. 2014). Santin and Doerr (2016), however, discovered that even very intense fires that consume most of the available below-ground and above-ground fuel may not affect soil, as this may only lead to limited heat penetration, unless fire is slow moving. Santin and Doerr (2016) indicated that soils are stable when soil temperature from biomass burning is below 100ºC.

The afore mentioned dynamics of soil-fire relationship are the most evident, although it is acknowledged that the fire attributes and environmental conditions in these experiments are not always explicit. Just as vegetation responds to fire, the effects of fire on soils also vary with space, as well as time and is usually heterogenous. At the plot and landscape scale some variations in fire effects on soils have been observed. Despite the general observation that hot fires (greater than 200ºC) can be detrimental to soil organic matter and reduce cation exchange capacity (Heydari et al. 2015), the concentration of nitrogen (N) in the soil has been reported to increase immediately after fire. Some studies, however, (e.g., Nardoto et al. 2003; Knowles et al. 2016) reported that the increase in N is temporary and that there is a decline in the levels of N after two years or more. The increase in N has been attributed to the intensity and frequency of burning (Neary et al. 1999). While nitrogen (N) could also be volatized at temperatures of 200°C, such temperatures enhance some soil nutrients such as calcium (Ca) from the ash (Neary et al. 1999).

Fire increased the rate of carbon mineralisation in burnt soils than unburnt Chaparral soils of Arizona and California (DeBano 1976). Chan and Heenan (2005), found that unburnt crop fields had higher organic matter than burnt crop fields in Australia. In the Guinea savanna of Ghana temperatures of 200ºC are reported to affect soils positively by increasing nutrient availability to plants and thus increasing plant productivity through increased supply of available nitrogen, phosphorus and sulphur (Bagamsah 2005; Kugbe et al. 2012, 2014). However, Santin and Doerr (2016) observed that at same temperatures of 200ºC, there is reduction of soil microbes and destruction of seedbanks and fine roots.

Relatively high levels of soil organic matter were observed in both burnt and unburnt woodlands in the Guinea savanna of Ghana (Amoako and Gambiza 2019). Whereas an annually burnt area recorded only 1.3% of organic matter an unburnt area had an organic matter content of 13.1%. (Korem 1985) in the same savanna. It is reported in the Lamto Reserve, Ivory Coast, that fire decreased soil water content, triggered grass growth and increased soil ammonium availability, which was probably caused by ash deposition and increased mineralization (Srikanthasamy et al. 2020).

Impeded filtration and percolation in soils are also attributed to the burning of above-ground litter, resulting in high water runoff in soils (Keizer et al. 2008). Impeded filtration and percolation are also known to reduce the capacity of soil to retain water, and likely to increase surface erosion. This condition is attributed to the removal of vegetation which increases soil exposure to raindrops, increasing breakdown of aggregates and dispersion of clay, resulting in soil crusting as was observed in Portugal (Keizer et al. 2008). Clays have high susceptibility to high temperatures through the irreversible deletion of hydroxyl ions (OH) and destruction of crystalline structure (Heydari et al. 2012) thus affecting the texture.

Contrarily, high temperatures during fire could modify aggregation of clay particles to the size of sand in Chaparral soils, thus increasing sand particles of the soil (DeBano et al. 2005). In relation to fire effects on soil texture, bulk density is another physical property that is affected as Heydari et al. (2015) reported that, bulk density increased as fire severity increased to medium and high levels.

Perceptions and knowledge of the uses of fire

Perception is about how people select and interpret information from their environment i.e., social, economic, traditional, natural, etc. which shapes their actions (Schermerhorn et al. 2000). The socio-cultural characteristics of people's attitudes toward the biophysical environment and natural resource uses, are reflected in their perceptions (Raish et al. 2007). As discussed earlier, most research conducted on the use of fire and the effects of fire on anthropogenic parklands are based on perceptions. Understanding people's knowledge and perceptions are therefore, crucial in the integration of local knowledge into management practices and policies on natural resource management at the local and national levels. However, previous studies (e.g. Muriuki et al. 2011; Vihervaara et al. 2012; Sinare et al. 2016) have focused on perceptions of natural resources degradation, other than the impact of anthropogenic fires on natural resources. According to Shackleton et al. (2018), an improved understanding of people's perception of natural resource management can reduce conflicts of interest, enhance dialogue and communication amongst stakeholders, by considering different knowledge systems.

Further, a study in Indonesia investigated perceptions of peatland fire across different governance levels (multi-stakeholder), ranging from local farmers to international stakeholders (Purnomo et al. 2017; Carmenta et al. 2017). The study observed that a multi-stakeholder approach enhanced the implementation of policies on fire in Indonesia (Carmenta et al. 2017). FAO (1998) reports that the perceptions of local people can build upon existing informal and formal resource management mechanisms that strengthen the capacity of local institutions and communities to promote sustainable resource management. It is therefore, becoming increasingly recognised that to achieve sustainable natural resource management, there is a need to achieve an interface among all stakeholders.

Conceptual framing of the thesis

In West Africa, a traditional system of farming occurs in savannas which is known as agroforestry parklands - a farming system in semi-arid and sub-Humid West Africa, where scattered multipurpose trees occur on farmlands as a result of farmer protection and selection, cover the vast majority of cultivated and bush fallows in Sahelian and Sudano-Guinean savannas. This is an age-old practice that has contributed to the forms, kinds and types of savanna ecosystems that exist in West Africa today (Boffa 1995, 2000).

Current parkland vegetation is a reflection of careful selection of economically important woody species. Species that are less preferred are removed for fuel wood and other domestic uses to make way for crop cultivation interspersed among economically important woody species (Baziari 2017). More often than not, parklands are characterised by their dominant woody species, which reflect different agrosystems and rural societies. For instance, *Elaeis guineensis* parklands are found in Benin and the north of Togo (Schreckenberg 1996) and *Vitellaria paradoxa* parklands are dominant in north of Ghana and Burkina Faso (Lovett and Haq 2000). However, there are some agroforestry parklands in Cameroon that have high diversity without a specific species dominance (FAO 1997). The agroforestry parkland system has supported farmers' livelihoods and cultures for centuries because of the diversity of plants - providing non-timber forest products and food crops for household consumption and surplus for sale (FAO 1997).

Agroforestry parklands are complex systems, influenced greatly by major land use systems which revolve around the use of fire for agriculture and other socio-economic activities. Fire is therefore a major tool in the performance of agroforestry parkland practices (Boffa 2000). Fire-assisted practices include using fire to burn grass and debris on farmlands instead of weeding or ploughing the dry grass, thus reducing labour costs. Also, hunting is done by burning the bush to flush out rodents, as well as attracting animal to trap game and natural pasture management by burning to stimulate fresh grass in the dry season. Few studies (e.g., Boffa 2000; Bagamsah 2005; Birnin Yauri and Aliero 2010) on agroforestry parklands of West Africa recognised fire as an important component of parkland management but the effects of fire are usually only mentioned in passing. For instance, Boffa (2000) gave an overview of parkland resources, conservation and management in Burkina Faso. Similarly, Asse and Lassoie (2011) assessed farmers' knowledge and management of soil fertility and vegetation in the Guinea savanna parklands of Mali – the study analysed the typology of farmer practices in the sustainable management of trees and soils. Other studies (e.g., Aleza et al. 2015, 2018) examined the regeneration of some economically useful species under different land use management regimes in Benin.

These studies and others on agroforestry parklands, have been silent or just mention in passing the effects of fire on population dynamics of economically important woody species such as *Adansonia digitata*, *Vitellaria paradoxa* and *Anogeissus leiocarpa* which are dominant species in the parklands. Yet, traditional fire regimes have influenced species survival and composition as well as soils in parklands. Again, there are very few studies on the effects of fire assisted land use practices on soils. Nonetheless, these woody species drive most rural economies and the soils are the source of nutrients for the sustenance of crop production and vegetation (Boffa 1999, 2000).

The gap in fire research on savanna parklands which comprise of woodlands, bush fallows, natural pastures and cropland requires an integrated approach that examines fire use and the impacts on vegetation, soils, as well as primary users' (actors) perspectives and the governance of agroforestry parklands. Studies on people's perceptions of fires and fire effects can also influence active policy decisions and intervention on fire use in the Sahelian, Sudanian and Guinean parklands of West Africa (Amanor 2002). This is of great importance because people are perceived to be the major determinants of fires in Africa (Knowles et al. 2016; Dwomoh and Wimberley 2017).

Social-ecological systems framework

The traditional system of farming in agroforestry parklands of Sahelian, Sudanian and Guinean savannas of West Africa have been maintained for many generations (FAO 1997). Thus, studies on anthropogenic fires in the agroforestry parklands of West Africa resonates with the social-ecological systems (SES) framework (McGinnis and Ostrom 2014; Brondizio et al. 2016). The SES framework is a guide to analysing the biophysical and social interactions of a social-ecological system at several spatial and temporal scales recognising the system's continuous adaptation to endogenous and exogenous factors. The model operates on a five-tier (Figure 2)

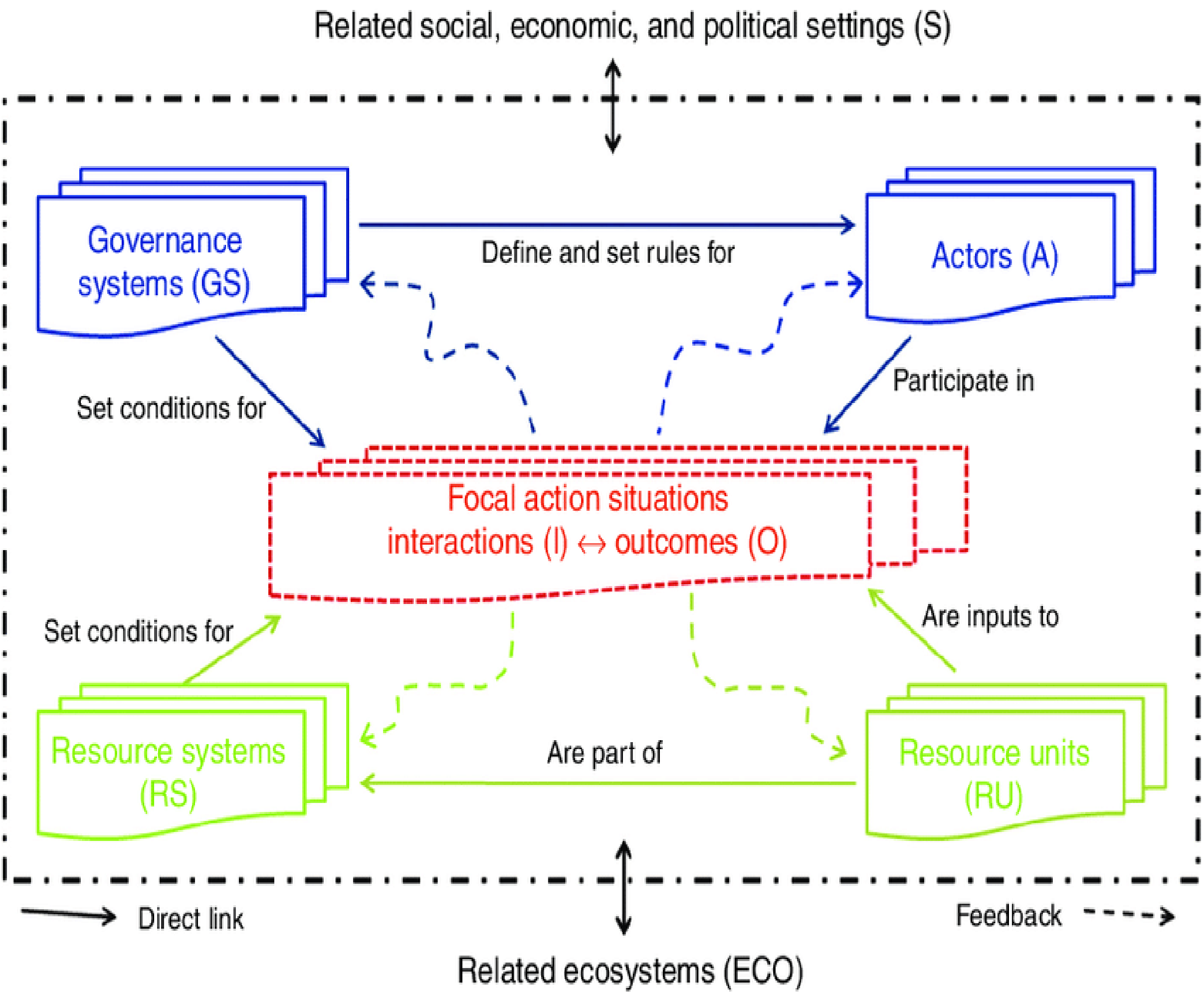


Figure 2. The five-tier social-ecological framework (McGinnis and Ostrom 2014)

The framework conceptualises humans, as part of nature, hence, empowers actors (A) - both formal and informal institutions to make information available on natural resources and common pool resources management in particular. The concept recognises that actors have control of how the resource units are extracted and used from the resource system. These processes in the SES are dynamic on common pool resources such as the parklands of West Africa. The SES draws on governance tier (GS) which examines processes and conditions to resolve conflict in resource use and enhance policy processes that affect the interactions (O) between social subsystems (humans, social and institutions) and ecological subsystems (RS and RU) (McGinnis and Ostrom. 2014; Delgado and Marín 2016).

The SES framework is adaptable and continues to change depending on the context (McGinnis and Ostrom 2014). However, in spite of the wide use of the SES framework, Stojanovic et al. (2016), reported a difficulty due to the inconsistencies in defining some social components, and setting spatial and functional boundaries using the framework by some researchers. The researchers admitted that the approach has weaknesses in capturing certain social realities such as individual motives and action. The authors iterated that in the application of the framework, components such as resource extraction, population, and material benefits, receive more consideration than equity, non-material, as well as psychological aspects of well-being.

Notwithstanding, the concept of the SES remains relevant because of the salient insights concerning the dynamics between humans and the environment and promoting the need for multidisciplinary approaches to resolve real world problems. The framework guides empirical data collection and analysis that points to variables that may be important for explaining self-organisation and collective action.

Thus, for a study on anthropogenic fires in traditional agroforestry parklands we set out to examine social-ecological factors influencing the agroforestry parklands, considering four of the McGinnis and Ostrom's five level variables: Resource Systems; Resource Units; Actors and Governance systems. All of these levels interact to inform the focal action situations at the centre of the framework. This study therefore, adopted Ostrom's (2007) framework that dichotomises complex SESs such as the agroforestry parkland of West Africa into the three (3) elements (resource systems, resource units and users). The framework is adopted to elucidate fire use and fire impacts in agroforestry parklands taking cognisance of different fire- assisted land uses. The study is defined by a set of measurable variables to evaluate their impact on the whole system by applying structural models and the interactions of fire and land use on woody species as well as soil, and how users (e.g., farmers and hunters) perceive fire use in the parklands.

It was important to analyse the fire effects on the Resource systems (Tier 1) which is presented as the Guinea savanna parkland and the Resource units (Tier 2) representing the vegetation and soils variables which were analysed quantitively (Torralba et al. 2018). The quantitative analysis of the ecological systems provides a reliable representation of reality of tree populations in agroforestry parklands. Analysis of stand level responses to early, late and no burn is discussed in Chapter three. In Chapter (four), the study sought to examine and ascertain how the frequency of fire use and different land uses affect the population parameters and structures of *Vitellaria paradoxa* and *Anogeissus leiocarpa.* It was important to ascertain the impacts of the myriad uses of fire around the world and West Africa in particular on soil in this region. All these analyses can enhance successful course of actions for the management of parkland systems for sustainability. People's perceptions (Tier 3) of the use of fire were also investigated in this regard. Thus Chapter 2 expounded the extensive knowledge, values, practices and perceptions of the traditional uses of fire in subsistence agriculture, as practiced in tropical savannas in Africa, and West African agroforestry parklands in particular which have been under estimated and thus received limited research attention. Thus, considering fire use and its influence on the resources system through assessment of feedback from the resource unit.

According to Baziari (2017), the traditional agroforestry parkland system that was considered sustainable, is showing signs of decline. Thus, the SES model as a holistic approach to understanding ecosystem structure and processes, can examine the factors of the system to understand the present and future impacts of disturbances such as fire on the social-ecological systems.

As a complex SES, traditional agroforestry parklands need user-centred studies to examine the knowledge and practices that drive the use and control of fire, and perceptions of fire regimes. Soliciting the perceptions and the knowledge of the users of fire and their influence on these resource systems is necessary to ensure an integrated study that enhances deeper understanding of experiences, phenomena and context of fire use in parklands. Studies (Folke 2006; Hilhorst 2008; Carmenta et al. 2017) have shown that integrating the different perspectives of the resource users in the management of resources can correlate positively with the sustainability of the resource. Thus, understanding the linkages and interactions between the fire users and fire use, effects of fire on the environment denotes the SES framework (Torralba et al. 2018). The output of the research can complement sustainable environmental management decisions and land use policy interventions of savanna in general and specifically to curb indiscriminate anthropogenic fires in agroforestry parklands.

The concept and typology of a fire regime

To understand the impacts of fire on ecosystems, the foundation and components of fire are critical. The extent and the nature of fire are characterized by multiple attributes - time, season, intensity, duration, type, shape, size of burn and a range of factors including topography, moisture content and prevailing weather conditions, and the availability of combustible materials (Gambiza et al. 2005; Kugbe et al. 2014). This explains how the concept of fire regime is not a characteristic of a single fire incident but the frequency bouts of a fire occurring over a long time, the season and the extent, type of the burn (Ruthven et al. 2003).

The characteristics of a fire regime are important in shaping savanna landscapes and the associated changes in vegetation, soils and other forms of life (Trollope and Trollope 2002). Myers et al. (2004) for instance, argued that savanna plants have varying degrees of resilience to fire: some are sensitive to fire intensity whilst others are most sensitive to fire interval.

Fire regime influences size, distribution and composition of vegetation, whereas the structure and type of vegetation determine the type and nature of fire (Trollope and Trollope 2002; Gambiza et al. 2005). The characteristics of wildfires are thus dependent on a wide range of drivers such as the fuel structure, and other disturbances, previous management system, and landscape characteristics (including topography and climate (Trollope and Trollope 2002; Gambiza et al. 2005).

Anthropogenic fires, play important roles in landscape management and heterogeneity and for agroforestry parklands more species are affected compared to a single-species agricultural of forestry system. Fire has selective effects on species and savannas, and the vegetation types therein, have varying degrees of resilience to fire regimes. Thus, fire classification is also based on its characteristics and behaviour, which includes cool and hot ground, surface, understory, crown, and mixed-severity (Trollope 2011; N'Dri et al. 2018). Fire frequency is the number of ignitions and how often fires occur in an area, vis-à-vis the interval and rotation (Govender et al. 2006; Penman et al. 2007). Research has shown that natural fires rarely occur in contemporary African savannas; humans have interfered and thus determine fire frequency, interval and rotation based on dominant weather patterns (Archibald et al. 2012).

Fire intensity is the rate of energy release during active burning. Intensity is proportional to the fire severity (Ruthven et al 2003). Intensity is influenced by fuel load, temperature, humidity and wind speed (spread of fire). Drivers of fire intensity differ from region to region, by day, month and year. Fires can be described as either cool or hot depending on the intensity (Trollope 2011).

Cool fires are usually an early dry season burn which usually occurs between November and January in West Africa. However, there are complexities in examining what is cool fire depending on a range of factors such the intensity which is in turn dependent of fuel load and region of occurrence. Hot fires are set later in the dry season, between January and March in the Sudanian and Guinean savanna. Then from July to September in the Southern Zambezian (Spinage 2012).

The use of fire in African savannas is usually determined by rain rather than temperature: early burning and late burning depend on the time of year (Spinage 2012). Thus, burning is dependent to a large extent on the time the rainy season ends. Early burning is done when vegetation is green, with relatively high moisture content. It is said to be usually mild, less destructive and easy to control (Trollope 2011) – (Figure 3). In late burning, fire is set when the vegetation is dry and provides enough dry matter for burning. This is more often difficult to control and may affect even fire-tolerant and fire-adapted species (Telly and Fiadjoe 1996).

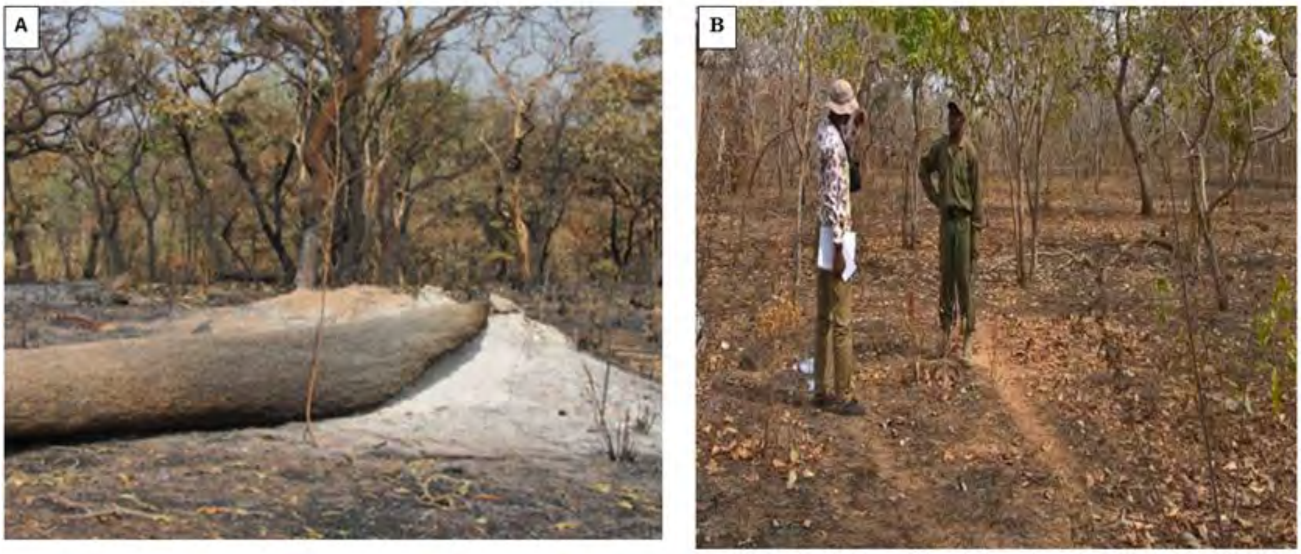


Figure 3. Early burnt areas in **A**-unprotected woodland and **B**-protected Guinea savanna woodland in the study area, Ghana. Photos by Esther Ekua Amoako - reconnaissance survey, 2016.

Burning practices are classified into three main groups (Trollope 2011). These are convenience burning, controlled burning and prescribed burning. Convenience burning only considers the place of burn and timing (Trollope 2011). It is usually not regulated and not managed. This is the practice carried out by most rural communities in the parkland of West Africa (Bagamsah 2005).

Controlled burning is the planned application and confinement of fire to a selected land area, commonly practised by crop and livestock farmers during the season of burn. This method of fire application cannot be said of poachers who burn large areas to flush out animals. Shaffer (2010) indicated that most people do control fires for land preparation. Prescribed burning, on the other hand is the planned burning of the selected land area when the weather and the vegetation favour a particular method (van Wilgen 2009). This method is largely used in protected areas in Africa as against traditional uses of fire. So, a fire regime may mean different things to different people - who use fire in managing of reserves and for traditional uses.

Rationale of the study

The Guinea savanna woodland of West Africa is the boundary between the forest zone and the Sudanian-Sahelian zone of West Africa. Although the Guinea savanna is distinctly defined by climatic and edaphic factors, major anthropogenic influences in this ecoregion include fire and cultivation (Veenendaal et al. 2018). Satellite imageries (Dwomoh and Kimberly 2017) have shown that burning reaches its peak during the annual Harmattan and dry season, which begins in November and ends in April, and is followed by the cultivation of crops for six months.

Land use and cover maps have also shown high conversion of woodlands to farmlands, which is done by traditional methods, including the use of fire (Shoyama 2018). Indeed, Shoyoma et al. (2018) reported that between 1984 and 2015, crop fields increased from 20% to 50%, whereas woodland and grassland decreased by 20% from 28%. Fire use would be a significant practice for the conversion of woodland into crop fields in the Guinea savanna. In Ghana, fire use for on-farm (food crop cultivation) activities and other livelihood activities dates back to pre-colonial and post-colonial times and has been an issue of public concern (Korem 1985; Amanor 2002). Kugbe et al. (2012) report that 46–60% of the Guinea savanna is burnt annually (Figure 4), with peak periods in December to January. Figure 4 shows the fire occurrence in Ghana and Northern region over a ten-year period (2001-2010).

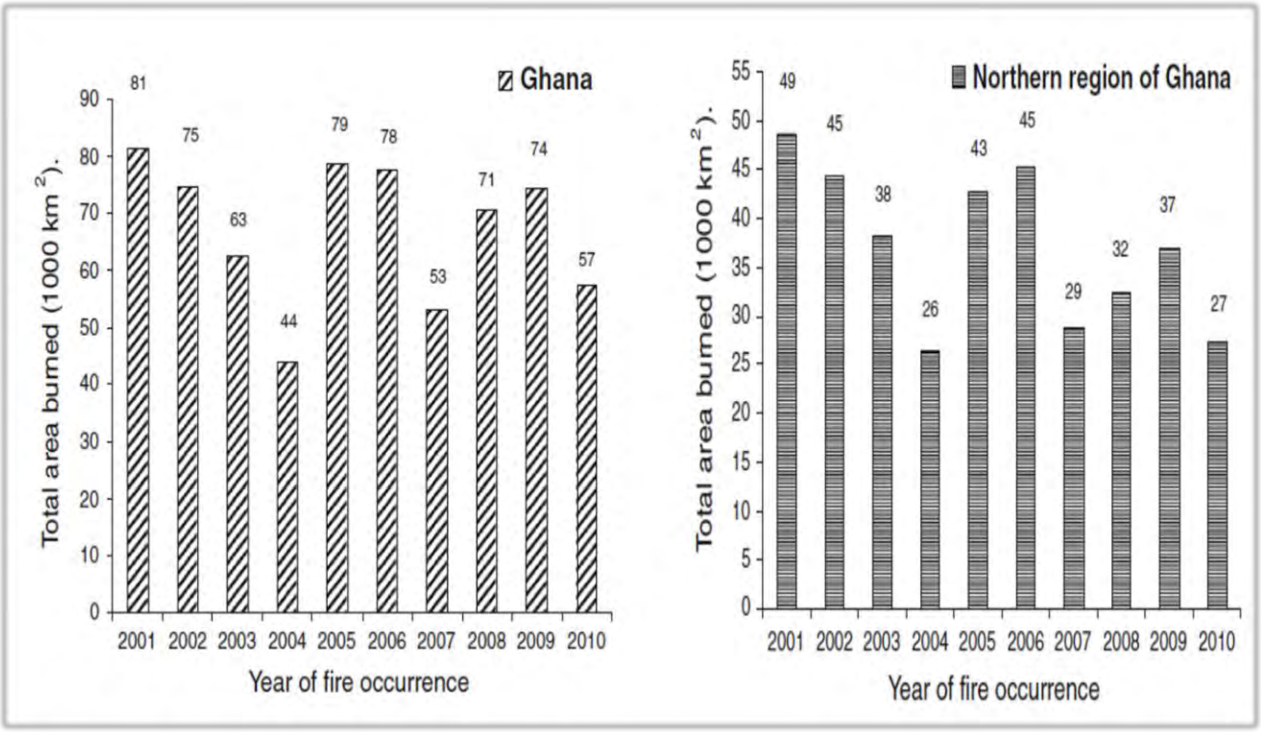


Figure 4. Fire occurrence in Ghana and Northern region (2001-2010)
Source: Kugbe et al. (2012).

Also, recent records of fire count (2013-2017) for Ghana obtained from Earth Observation Research and Innovation Centre, University of Energy and Natural Resources (EORIC/UENR), Ghana, showed high fire frequencies for the Guinea savanna with an increasing trend compared to previous data as that reported by Kugbe et al. (2012) - Figure 4.

Against this backdrop, it is vital to understand the effects of recurrent fires on economically important woody species and soils in woodlands and farmlands. These woody species such as *Vitellaria paradoxa* play important roles in meeting the needs of the local people as well as the provision of other ecosystem services (Bagamsah 2005). It is also essential to appreciate what knowledge systems pertain to fire use in agroforestry parklands.

Studies have shown that some preferred and economically important woody species are deliberately protected from cutting and other forms of destruction (Blench 2001). However, the annual dry season fires could pose a major threat to these savannas/parklands. It is therefore important to understand the effects of fire on woody species as well as soils. Fire use in these agroforestry parklands remain understudied, so that knowledge gaps on fire use are not always easily identified. It is important to examine fire use and primary users' perspectives in the management of savannas and parkland of West Africa.

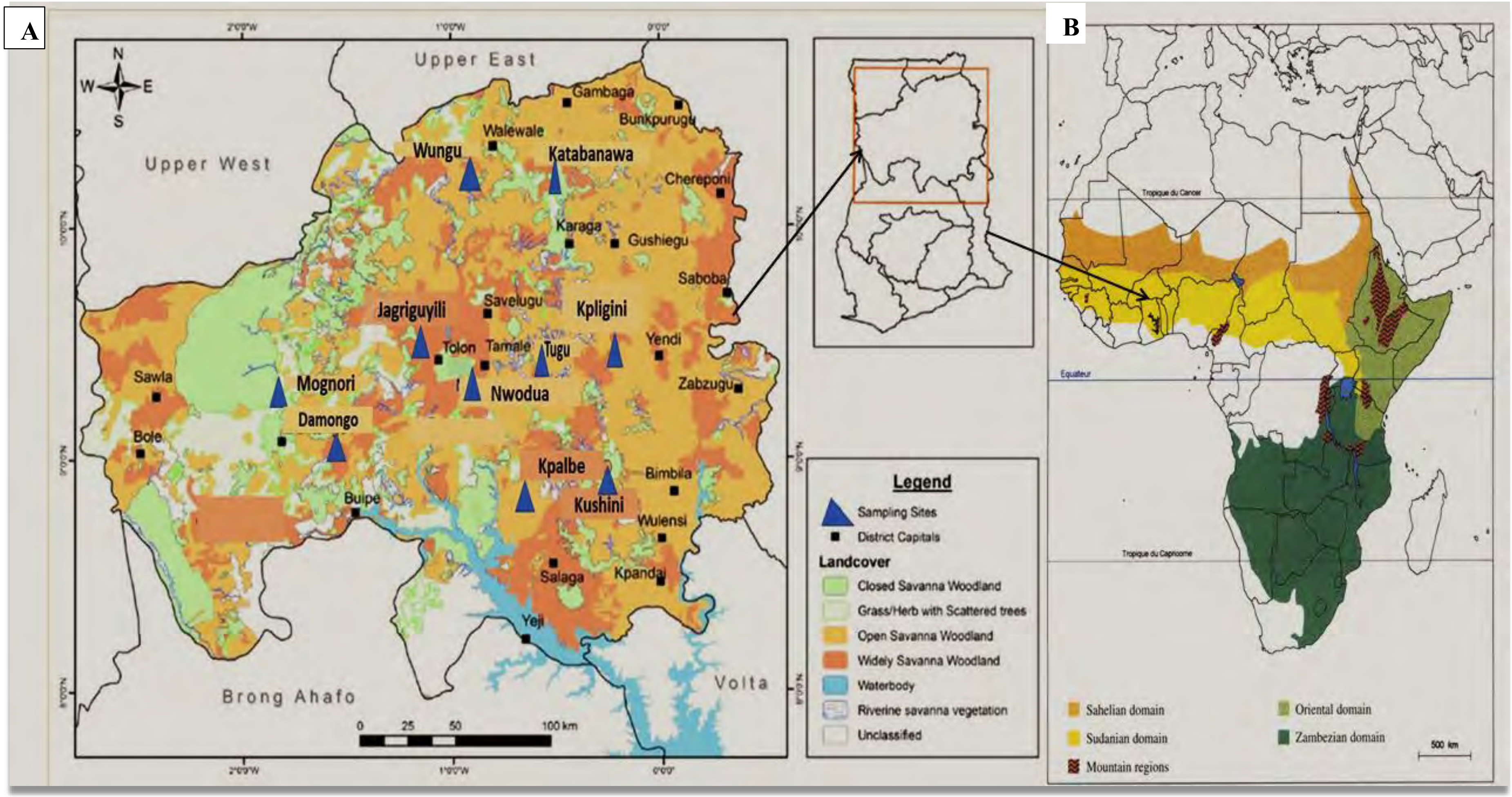
Aims and research questions

This study aimed to contribute to the understanding of fire effects on vegetation and soils in six common land use types in the Guinea savanna as well as local people's knowledge, practices and perceptions of the use of fire. Answers were therefore sought to the following specific research questions which form the basis for the four empirical Chapters:

1. What are peoples' knowledge and perceptions of their use of fire?
2. How does the time of burning influence the composition of tree species?
3. How does fire influence the population structure and abundance of economically important woody species?
4. How does fire influence soil properties?

Description of the study area

The Northern region of Ghana, lying mostly between 8-10° N and 0-2° W, occupies an area of about 70,383 km^2 (Dwomoh and Wimberly 2017). It is the largest region in Ghana in terms of land area. The region shares boundaries with the Upper East and the Upper West regions to the north, the Brong Ahafo and the Volta regions to the south (Figure 5). The land is mostly flat, with an altitude of about 150 m above sea level.



Sources: Adapted from Amoako et al. (2015). Source: Fauvet, N. (1999).

Figure 5. **A** -Vegetation map of Northern region, Ghana, showing study sites and **B** - location of Ghana in vegetation of map Africa

Climate

The study area lies between sub-humid and semi-arid zones in terms of the climatic regime (Kranjac-Berisavljevic et al. 1999). Thus, the region is relatively dry. The amount of rainfall recorded annually varies between 750 and 1,050 mm (Kranjac-Berisavljevic et al. 1999). The temporal distribution of rainfall is unimodal, with the rainy season beginning in May and ending in October. The dry season starts in November and ends in March/April. Maximum temperatures (~ 40°C) occur towards the end of the dry season and minimum temperatures in December and January, with an annual mean temperature of 25°C.

The Harmattan wind blows from the Sahara Desert (from north-east towards south-west) from December to early February and has a considerable effect on the temperatures in the region. The weather during this period is relatively cool and dry at the beginning of the season but increasingly becomes very hot and dry as the rainy season approaches. During the Harmattan, the relative humidity may drop to as low as 10% due to extreme dryness of the wind laden with dust particles (Kranjac-Berisavljevic et al. 1999).

Soils

Geologically, the area consists of Proterozoic rocks referred to as the Birrimian formation, which vary in lithology and the degree of metamorphism (Pelig-Ba et al. 2003). Granite and metamorphic rocks are the main rock types and include biotite schists, biotite-horn-blande gneisses, garnet-hornblende and garnet-biotite gneisses and schists. Others include albite-chlorite, sericite-quartz schists with interbedded acid tuffs, manganiferous phyllites and sandstones as well as laterites. These are locally referred to as savanna Ochrosols (Pelig-Ba et al. 2003) and Luvisols/Lixisols in "World Reference Base for Soil Resource" (Mikkelsen and Langohr 1998).

In some areas, there are iron concretions a few centimetres below the surface of the soil. The texture of the soil is silty to sandy loam. The soils are comparatively low in organic matter (Owusu-Bennoah et al. 1991). Luvisols are moderately drained and less prone to degradation than the sandy soils. Valley bottoms contain more of fertile soils suitable for the cultivation of rice and vegetables (Mikkelsen and Langohr, 1998; Owusu-Bennoah et al. 1991).

Vegetation and fauna

The vegetation cover is Guinea savanna which is predominantly woodland savanna consisting of mixed formations of densely wooded and isolated, medium-sized fire and drought-resistant tree, shrub and grass species (Kranjac-Berisavljevic et al. 1999). The vegetation is, characterised by trees such as the *Vachellia and Senegalia* spp., *Adansonia digitata* L, *Vitellaria paradoxa, Parkia biglobosa* (Jacq.) G.Don. and *Ceiba pentandra* (L.) Gaertn. and interspersed with tall and short grasses depending on land use types. *Andropogon gayanus* Kunth, *Sporobolus pyramidalis* P. Beauv, *Heteropogon contortus* (Linn.) P Beauv., *Dactyloctenium aegyptium* (Linn.) P. Beauv, *Chrysochloa hindsi*, C. E Hubbard and *Imperata cylindrica* (Linn.) are the common grass species found in the Guinea savanna (Blench 2001). The natural vegetation is gradually transformed as numerous tree species have been deliberately removed from the parklands (Lovett and Haq 2000). Thus, the Guinea savanna is gradually mimicking the Sudan savanna - characterised by sparsely populated woody species with higher grass cover in previously wooded areas. The annual bushfires are contributing to the decreasing number of woody species (Blench 2001). However, government-protected areas such as the Mole National Park and sacred groves found in study communities are deemed to be replica of the original or natural Guinea savanna ecosystem (Campbell 2005).

The Mole National Park is home to a wide variety of ungulates such as *Kobus kob, Kobus Ellipsiprymnus* (Waterbucks) *Hippotragus equinus* (Roan), *Hippos*, *Cephalophus natalensis* (Duikers), *Alcelaphus buselaphus* (hartebeest), *Phacochoerus africanus* (Warthogs) and *Loxodonta africana* (Elephants), as well as variety of bird species. The Park has a total of 32 rural communities (Abukari and Mwalyosi 2018). The Park is pressured and threatened by poaching and annual bush fires from neighbouring these fringe communities (Abukari and Mwalyosi 2018).

Social-demographic setting

The Northern region has a population density of 37 persons per square kilometre. Most inhabitants (52%) speak a language of the Oti-Volta sub-family in the Niger-Congo language family, such as Dagbani, Konkomba and Mampruli. The Dagbon kingdom, of the Dagomba people, is located in the region. The predominant languages that are spoken in the region are Dagbani, Gonja and Mampruli. The other languages are, Basaare, Chamba, Chokosi, Chumburu, Kantosi, Likpakpa, and Moar (Ghana Statistical Service 2010).

The region has a population of 2,479,461 persons: 49.5% (1,229,887) are males and 50.5% are females (1,249,574) with a higher annual population growth rate of 3.7% between 2010 and 2021 than the national growth rate of 2.1%. Of the total population, the youthful population aged less than 15 years is 44.9%. The population aged 15-64 years constitute 51%, whereas persons aged 65 years and older constitute 4.4% (Ghana Statistical Service 2010). The average household size in the region is 8 persons. The reasons for the large household sizes in the region are polygyny, high fertility and a common practice of nuclear and extended family members living together.

The Northern region has a low level of school attendance of children of primary school age at 59%. It also has the lowest female literacy rate in the country at 44% of young women aged 15–24 years (Ghana Statistical Service 2010).

The region is well known for its architecture of round huts with conical thatched roofs which are built in clusters for families. Around the cluster of huts are family farms known as compound farms (Gyasi et al. 1995; Ghana Statistical Service 2010). Among the historical sites that throw considerable light on the history of the people of the region, are the archaeological sites at Yikpa Bonso, in the West Mamprusi district, with relics of the Koma civilisation dating back to the 9th century (Gyasi et al. 1995; Ghana Statistical Service 2010)

Agricultural systems

Agriculture accounts for more than 90% of household incomes and employs more than 70% of the population in the region (Ghana Statistical Service 2010). It is mainly rain-fed, albeit with a few irrigation sites, and production is mainly for subsistence. The farming system usually involves a combination of growing food crops and keeping animals for multiple purposes. Among the major crops grown are maize (*Zea mays*), millet (*Panicum miliaceum*), rice (*Oryza sativa*), yams (*Dioscorea* spp.), cassava (*Manihot esculenta*), and various pulses and vegetables.

The farming practice in the Sudano-Guinean savanna follows a traditional agroforestry system where staple crops are cultivated among indigenous economically valuable trees for about 6-8 years (Gyasi et al. 1995). The cropped fields are allowed to rest for a fallow period of about 7-10 years to replenish soil fertility by natural regeneration after several years of continuous cultivation (Karbo and Agyare 1997). Cropping is also done around the home compounds, valleys and water bodies. These compound farms are usually permanent because the soils are replenished by the continuous supply of household waste and manure from livestock (Gyasi et al. 1995).

The major staple foods (maize, millet, yam) are grown by families for consumption at home and for sale and are managed by men. Women usually grow vegetables on marginal lands or intercropped in the compound farms. In most rural communities of the Northern region, women are engaged in farming activities which include a wide variety of small-scale agro-processing for the local market as well as for home consumption (Adjei-Nsiah- 2006). In addition to the cultivation of crops, the rearing of cattle, sheep, goats and fowls is an integral component of agricultural systems in the Northern region.

The growing population is reducing the length and frequency of fallow periods in some areas, thereby reducing the resilience of the land (Songsore 1996). The application of animal manure to increase soil fertility is common, although the use of chemical fertilizer is regarded as more convenient (Karbo and Agyare 1997). The hoe is the most essential implement used for work on the farm, although the use of bullock- and tractor-drawn ploughs for land preparation has increased in the last 30 years (Gyasi et al. 1995). There are also considerable parkland areas which have not been cultivated, either because of low soil productivity or left to lie fallow for a very long period as agriculture in the area is changing from shifting cultivation to a more sedentary system (Gyasi et al. 2004).

General approach to the study

The study employed a mixed-methods approach, using ecological surveys and measurements, laboratory analysis and socio-economic surveys. This mixed methods approach was used to determine the effects of fire on vegetation and soil, as well as people's perceptions and knowledge about the cultural and traditional use of fire in livelihood practices. The integration of these methods was necessary to unravel the complexities of human (mainly farmers) interaction in agroforestry parklands. Using the SES framework encourages interdisciplinary research which ascertains science–society interface as observed in this study. In this study for instance, although the focus is assessing the impact of fire in parklands, the study concentrates on soils, vegetation in protected and unprotected (different land uses) as well as drawing some knowledge on fire use from the prime users of fire in the Guinea savanna parklands of Ghana. These mix method approach embedded in the SES could address pressing sustainability issues on anthropogenic fires in these savanna parklands,

Thus, in order to identify people's perceptions of the use of fire, questionnaires were administered in six districts - categorised into high, moderate and low-frequency fire use districts. A reconnaissance survey was done with the leaders of some selected communities in the study area, to discuss site selection for the sampling. The abundance, density, size and classes of woody species in burnt and unburnt crop fields, burnt and unburnt woodlands, fallow and sacred groves were measured to determine fire impacts on vegetation. Standardised methods for species identification, density and composition were used.To determine fire effects on soils, samples were collected from burnt and unburnt land use types and soil properties analysed in a laboratory.

Structure of the thesis

This thesis consists of six chapters: beginning with a general introduction chapter (Chapter 1) followed by four results chapters (Chapters 2-5) and ending with a general conclusion - Chapter 6. The four empirical chapters are stand-alone and are based on individual research questions. These are in the format of scientific papers. Thus, there are repetitions of some sections in methods of the chapters. The reference styles for each chapter differ according to the requirements of the journals to which the chapters were submitted.

Chapter 1 presents the background of the study with an embedded literature review on African savannas, fire use, effects of fire on vegetation, soils, the conceptual framing of the research, the aim of the research, and study area.

Chapter 2 presents traditional practices, knowledge and perceptions of fire use in the Guinea savanna parkland.

Chapter 3 illustrates how the season and time of burning affects species composition in a protected area.

Chapter 4 presents the effects of fire on the population structure and abundance of *Anogeissus leiocarpa* and *Vitellaria paradoxa* in six land use types in the Guinea savanna of Ghana.

Chapter 5 describes the effects of fire on some soil properties and the implications of the high fire frequency for the study communities.

Chapter 6 is a synthesis of all the chapters, providing a conclusion with recommendations.

List of published papers

1. Amoako E.E. and Gambiza, J. 2022. Fire use practices, knowledge and perceptions in a West African savanna parkland. PLoS ONE 17(5): e0240271. doi.org/10.1371/journal.pone.0240271
2. **Amoako, E. E.** and Gambiza, J. (2021). Effects of fire on the population structure and abundance of *Anogeissus leiocarpa* and *Vitellaria paradoxa* in a West African savanna parkland. Acta Oecologica 112, 103745. doi.org/10.1016/j.actao.2021.103745
3. **Amoako, E. E.** and Gambiza, J. (2019) . Effects of anthropogenic fires on soil properties and the implications of fire frequency for the Guinea savanna ecological zone, Ghana, Scientific African, 6(2019), 11. doi: 10.1016/j.sciaf.2019.e00201

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CHAPTER 2: TRADITIONAL PRACTICES, KNOWLEDGE AND PERCEPTIONS OF FIRE USE IN A WEST AFRICAN SAVANNA PARKLAND

Abstract

Understanding people's practices, knowledge and perceptions of the use of fire and fire regimes can inform fire management plans that could contribute to savanna conservation and sustainable management. We investigated the frequency of fire use, control and perceptions of fire regimes for selected livelihood and socio-cultural activities in six districts in the Guinea savanna of Ghana. The six districts were selected to have a good representation of fire prone areas in the region based on fire frequency data obtained from the CSIR Meraka Institute, South Africa. The study revealed that the majority of respondents (83%) across the study districts used fire once a year for at least one of the following activities: land preparation, weed/pest control, burning postharvest stubble, bush clearing around homesteads, firebreaks, charcoal burning and hunting. The study showed a higher frequency of fire use for land preparation for cropping than for the other activities. Less than a fifth of the respondents (17%) indicated that they do not use fire for any of the selected activities. The majority of respondents (65%) mentioned that they controlled their use of fire to prevent destruction to property or injuring humans. The study showed a higher frequency of fire use in the dry season for land preparation for cropping. However, respondents rated season of burning as the most important attribute, with little attention to the other attributes of a fire regime, contrary to what is theoretically recognized. Understanding traditional fire use practices in terms of how to regulate the mix of frequency, intensity/severity, season, size and type of fire for these and other socio-cultural purposes could help to mitigate and/or to manage bushfire in West African savannas and enhance savanna conservation and sustainable management. Hence, the need to better understand people's knowledge and perceptions of fire regimes in fire assisted socio-cultural practices in West Africa.

Keywords: fire control, fire regime, fire use, Guinea savanna, socio-cultural practices

Introduction

Historically, humans in many regions have used fire extensively for various land use practices such as agriculture, hunting, foraging and pasture management, which has created diverse habitats and landscapes (Sara and Henrick 2002; Bassett 2003; Luoga et al. 2004; Eriksen 2007; López-Merino et al. 2009). The use of fire may be prescribed, controlled, uncontrolled or unintentional, depending on the source of the fire and the purpose of use (Shaffer 2010; Fernandes et al. 2013). It is reported that up to 7% of the world's population use slash and burn agriculture which has been practised for about 12,000 years (Ockwell and Lovett 2005; Pandya and Salvi 2017). Adar-burning, fire fallow, chitemene and swidden are all terms used for the slash and burn processes used during land preparation before cropping in different regions of the world (Shaffer 2010; Yokoyama et al. 2014; Day et al. 2014; Pandya and Salvi 2017). The practical details of slash and burn may differ from one place to another depending on local social and environmental conditions, but the purpose is mainly for crop and animal husbandry.

Traditional agriculture and other land-based socio-economic activities (e.g., honey hunting, game hunting and charcoal making) have been the source of food supply and income for both rural and urban economies of most countries of sub-Saharan Africa (Bassett et al. 2003; Agyeman et al. 2012). In fire-prone West African savannas, use of fire is integral to socio-cultural practices that are important for rural livelihoods and associated socio-economic activities (Archibald and Bond 2003; Dwomoh and Wimberly 2017). The savannas provide land resources referred to as agroforestry parklands where the bulk of cereals, grains and livestock are produced, usually by means of traditional methods of agriculture (Boffa 1995; Schreckenberg 1996; Boffa 2000).

The parkland system is a traditional system of agro-silvo-pastoral system where crops are cultivated and animals kept among indigenous tree species. Fire is used in these parklands to clear the land of vegetation for cropping, to burn postharvest stubble, as well as for weed management (Amissah 2010; Sluyter and Duval 2016; Nyongesa and Vacik 2018). Also, pastoralists in these parklands and woodland savannas have often used fire to control pests and to stimulate fresh grass growth in the early part of the dry season (Bassett et al. 2003; Coughlan 2013). Many rural people in these savannas still depend on hunting as a traditional livelihood strategies to supplement household income and protein needs (Adongo et al. 2012; Lindsey et al. 2013; Day et al. 2014; Nyongesa and Vacik 2018). A common method of hunting in the savanna is the use of fire to flush out animals or by burning early in the dry season to attract animals to the new growth where they can be hunted (Walters et al. 2014).

[1]Other studies have reported that fire is also caused by honey hunters, arson, careless disposal of cigarettes and children trying to mimic their parents use of fire (Shaffer 2010; Archibald 2016; Nyongesa and Vacik 2018; Ricketts and Shackleton 2020).

Similar to traditional burning in Australia and some parts of the world, Huffman (2013) explains that, these fires are used to achieve multiple livelihood purposes. The fires are set to whole farmlands for cropping, woodlands to open up new areas for new farms, as well as for hunting. The fires consume dead and dying grasses, tree litter, shrubs, small trees. In West Africa, these fires are usually difficult to control during the Harmattan (North-Easterly wind characterised by very low humidity and relatively high windy conditions occurring between November and April). Fires left uncontrolled during this period, may result in large and persistent fires (Laris 2011; Abukari and Mwalyosi 2018).

Satellite images of the West Africa savanna, as well as ground truthing, have shown that burning reaches its peak in the early to mid-dry season (November to January) (Devineau et al. 2010; Dwomoh and Wimberly 2017). Devineau et al. (2010) asserts that late season fires are observed in agricultural lands and wetlands. Thus, the evidence is that the fires are anthropogenic (Kugbe et al. 2014; Abukari and Mwalyosi 2018; Ramo 2021) and are usually made on small farms for cropping, as well as for hunting, charcoal making and other socio-cultural activities. Small fires from croplands in Africa, for instance, accounted for 41% of overall global burnt area per annum (Ramo et al. 2021). Thus, these fires are likely to have significant effects of fire impact at the landscape level and on the global environment (Devineau et al. 2010).

There are some regulations on bushfires in West Africa, that range from restrictive to less restrictive. The P.N.D.C. Law 229 (Bush Fire Prevention and Control Law, 1990) of Ghana for instance, indicates that if an action of a person results in the uncontrolled burning of a farm, forest or grassland, the person is liable on conviction to a fine (Ashon 2002). The fine is 1. Not less than two hundred and fifty penalty

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units and not more than one thousand penalty units or 2. To a term of imprisonment or community labour not exceeding twelve months or 3. To both the fine and the imprisonment or community labour. For a subsequent offence it can be a term of imprisonment or community labour not exceeding two years. However, the view among environmentalists in Ghana, is that the implementation of the law has not been proactive. Thus, indiscriminate bush burning continues to be practiced in most rural areas of Ghana (Amanor 2002; Ashon 2002; Songsore 2003). The challenges in the implementation of the law have been attributed to the lack of resources by the Forestry Commission and the Environmental Protection Agency to enforce the legislation, as well as the lack of stakeholder involvement in the enactment of the law (Amanor 2002; Ashon 2002). However, a few district assemblies in collaboration with the Agricultural Extension and Education unit of the Ministry of Agriculture, non-governmental organisations through non-formal education services have chalked some successes in implementing no-burning by-laws through the formation fire management squads in some communities in the Upper East and Northern regions of Ghana (Amanor 2002).

In neighbouring Burkina Faso, there are decrees on the use of fire in rural lands which make precise authorisation or prohibition of the use of fire according to the circumstances. Bushfires are prohibited, but management fires (controlled burning for agricultural purposes) and customary fires managed by a traditional authority and village land management committees are allowed (Makela and Hermunen 2007). These decrees have worked quite well since 1997, because the traditional authority has played key roles in the management of fires in the country (Makela and Hermunen 2007).

Studies on fire use in savannas have focused on the management and impact of fire on the environment (Russell-Smith et al. 1997; Bagamsah 2005; Beringer et al. 2007; Bento-Gonçalves et al. 2012; Kugbe et al. 2014). However, some research has focused on understanding people's knowledge, practices and perceptions of 'fire-assisted' livelihood activities (e.g., Mistry 1998; Russel-Smith et al. 2001; Eriksen 2007; Angassa and Oba 2008; Shaffer 2010; Huffman 2013; Fernandes et al. 2013; Nyongesa and Vacik 2018). Nevertheless, the extensive knowledge, values, practices and perceptions of the traditional uses of fire in subsistence agriculture, as practiced in tropical savannas in Africa, and West African agroforestry parklands in particular, have been under estimated and thus received limited research attention.

Thus, in consonance with Eriksen's (2007) research on "Why do they burn the bush"? It was important to gather information on people's knowledge and perceptions on fire in the Guinea savanna of West Africa where traditional agriculture is embedded in the parkland system. Understanding how people perceive the role of fire in their socio-cultural and livelihood activities is necessary to inform fire management plans so that they are well-matched with local knowledge, fire use practices, as well as traditional land use systems (Russell-Smith et al. 2001; Raish et al. 2005; Archibald 2016; Mistry et al. 2016). This could contribute to conservation and sustainable management of savannas of Africa. Thus, the objective of the study in line with the theoretical framing of this thesis was to investigate peoples' practices, knowledge and perceptions of the traditional uses of fire. Answers were sought to:

1. What are the relationships between fire use and the selected socio-cultural activities?
2. How frequently is fire used for the selected socio-cultural activity?
3. How often is fire controlled for the selected activities?
4. What are people's perceptions and knowledge of a fire regime as defined by Bond and van Wilgen (1996) and Keeley (2009)?

Methodology

Background and setting of the study area

The study was conducted in the Northern region of Ghana, located in the Guinea savanna ecological zone (9.5439° N, 0.9057° W). The climate of the region is tropical with a unimodal rainfall distribution, with an annual mean rainfall of 1,100 mm (Ghana Meteorological Service 2017). Thus, the region has only one cropping season that falls between May and October (Gyasi 1995). The peak of the rainy season ranges between July and September, with the rainfall exceeding potential evaporation over a relatively short period (Boubacar et al. 2005). The mean annual temperature is 27°C. The region experiences comparatively high annual potential open-water evaporation of 2,000 mm. Due to its proximity to the Sahel, the region experiences dry, dusty north-easterly winds (Harmattan) between November and April, which facilitates the annual vegetation burning (Kranjac-Berisavljevic et al. 1999) across all the districts in the region. The area is characterised by large areas of natural pastures with grass species from the sub-families of Andropogoneae and Paniceae (Andersson et al 2003; Bocksberger et al. 2016), interspersed with fire and drought-resistant woody species from the families Fabaceae and Combretaceae (Bagamsah 2005; Amoako et al. 2018).

Population

The region has a population of nearly 2.5 million people, representing ten percent of the total population of the country (Ghana Statistical Service 2010). The population density is 37 persons per km^2 (Ghana Statistical Service 2010). The majority of the population lives in rural areas. The region has five paramount chiefdoms (traditional areas), namely, Dagomba, Gonja, Mamprusi, Mo and Nanumba. Each traditional area represents a major ethnic group in the region (Jönsson 2007). The population of these groups varies, with the largest group being the Dagomba which constituting 30% of the regional population. The Gonja and Mamprusi groups comprise over 7% of the population (Ghana Statistical Service 2010).

Agricultural systems

Agriculture contributes more than 90% of household income and employs more than 70% of the population in the region (Ghana Statistical Service 2010). Approximately 80 to 90% of all land in Ghana is customary land, giving the highest-ranked chief the absolute right of possession, transfer and lease. Agricultural lands in communities have been transferred from generation to generation within a clan. This customary land tenure system is recognised by the Constitution of Ghana (Tomomatsu 2014).

The farming system is traditional agroforestry, which is usually a combination of growing food crops and keeping animals for multiple purposes. Farm sizes of one to two hectares (Gyasi et al. 1995) are located around one to six kilometres from the compound house (Karbo and Agyare 1999). Families may cultivate one or more farm holdings depending on the availability of land in the community. Crops are cultivated for about five to ten years interspersed among economically valuable indigenous tree species, a system of agriculture which is commonly referred to as agroforestry parklands (Boffa 1995). The crop fields within parklands are allowed to rest for a fallow period of about three to five years to replenish soil fertility after several years of continuous cultivation.

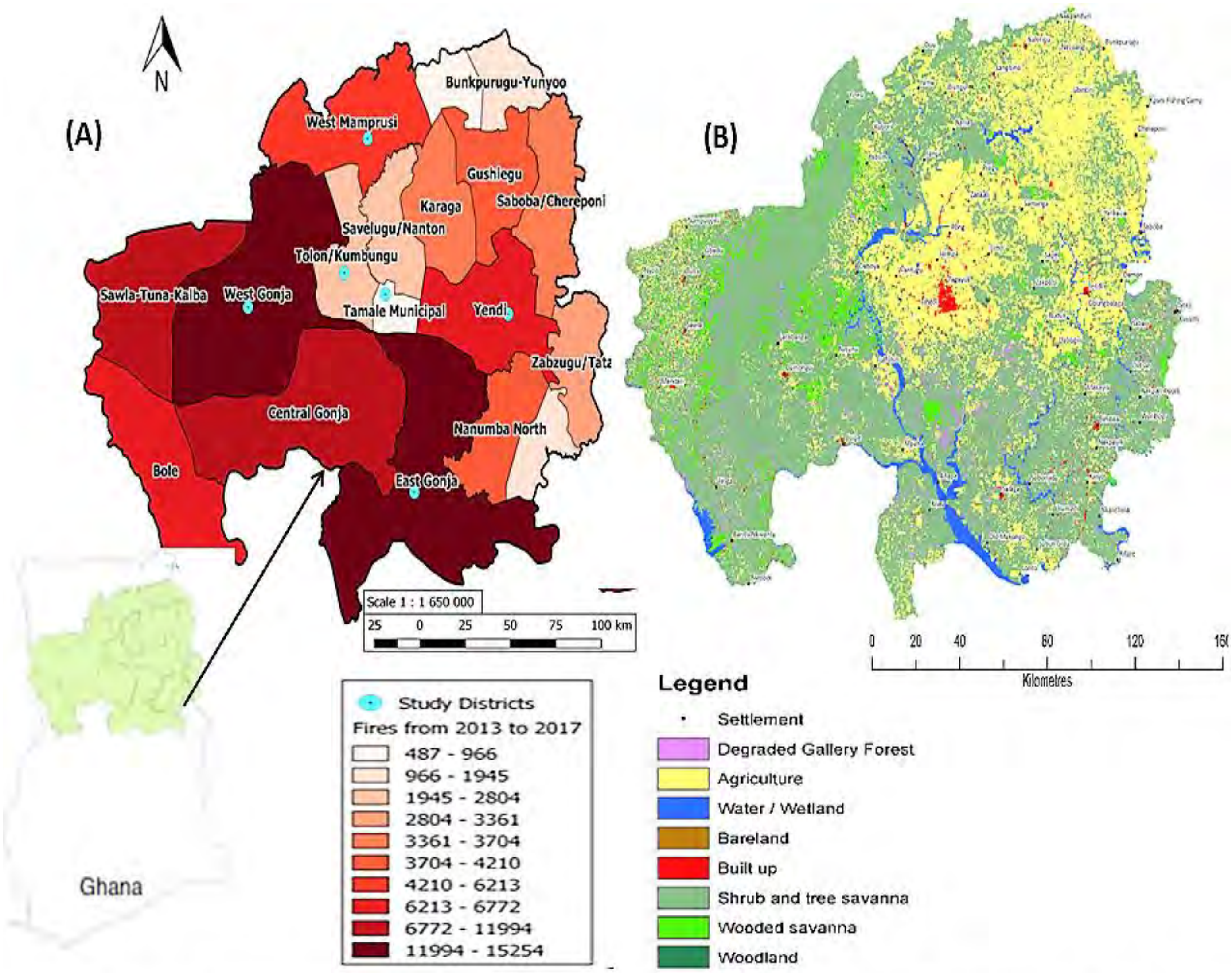
Among the major crops grown are maize (*Zea mays*), millet (*Panicum miliaceum*), rice (*Oryza sativa*), yam (*Dioscorea* spp.), and various pulses and vegetables (Gyasi et al. 2004; Brookfield and Gyasi 2009). Cropping is also done around the home compounds in the rainy season and in valleys adjacent to water bodies, especially in the dry season (Gyasi et al. 2004). These compound farms are usually permanent, because the soils are replenished by the continuous supply of household waste and livestock manure (Karbo and Agyare, 1997). They are also burnt annually to control ticks and reptiles, as well as for visibility purposes (Gyasi, et al.2004). There are considerable areas of parkland which have not been cultivated, either because of low soil fertility or they have been left fallow for a very long period (Oppong-Anane, 2006).

The Northern region leads in livestock (ruminants and poultry) production in the country. Livestock is kept on both free range and semi-intensive systems by households and hired Fulani herdsman, respectively (Karbo and Agyare 1997). Other socio-economic activities are agro-processing (e.g., rice and groundnut processing) and the processing of non-timber forest products (NTFPs) (e.g., shea butter processing).

Data collection

Sampling design

Stratified, purposive and convenience sampling techniques were used. Data on daily fire counts (detected by sensors on Earth observation satellite) from 2013 to 2017 on Ghana, were received from EORIC (Earth Observation Research and Innovation Centre Ghana) in collaboration with the Advanced Fire Information the CSIR, Meraka Institute South Africa. The first batch of fire data for the 2015 to 2017 was sent from EORIC, and data for 2013 and 2014 from the CSIR (Amoako and Gambiza 2019). The fire count data for 2013 to 2017, was used to generate a fire map for the region (Figure 1 A) which is compared to the land use/land cover map of the region (Figure 1 B). The two maps show the link between fire frequency, vegetation and land uses in the Guinea savanna ecological zone. Eighteen districts in the Northern region of Ghana with data on fire counts were categorised into high fire frequency (6,213-15,254 counts), moderate fire frequency (2,804-6,213 counts) and low fire frequency (487-2,804 counts) districts (Figure 1 A).



(A) Fire map - Field data 2017 (CSIR Meraka Institute) **(B)** Land use map 2017 - SERVIR/CERGIS/USAID/NASA

Figure 1: **A** - Fire frequency gradient (colour gradient), and selected study districts, **B** - Land use map of study area for 2017.

To have a good representation of high, moderate and low fire prone areas in the region, six of the 18 districts and 10 study communities (Figure 2) were purposively selected for the survey with the help of the Regional Forestry office. The communities selected were Damongo Canteen and Mognori (West Gonja district), Kpalbe and Kushini (East Gonja District) were selected in the high fire frequency districts, Kata-Banawa (West Mamprusi district), and Kpligini (Yendi district) in the moderate fire frequency districts and Jagriguyilli and Nwodua in the Tolon, Kumbungu district, Tugu (Tamale South Municipality) in the low fire frequency districts. Tugu and Damongo Canteen are peri-urban communities, while the remaining eight are rural communities (Figure 2).

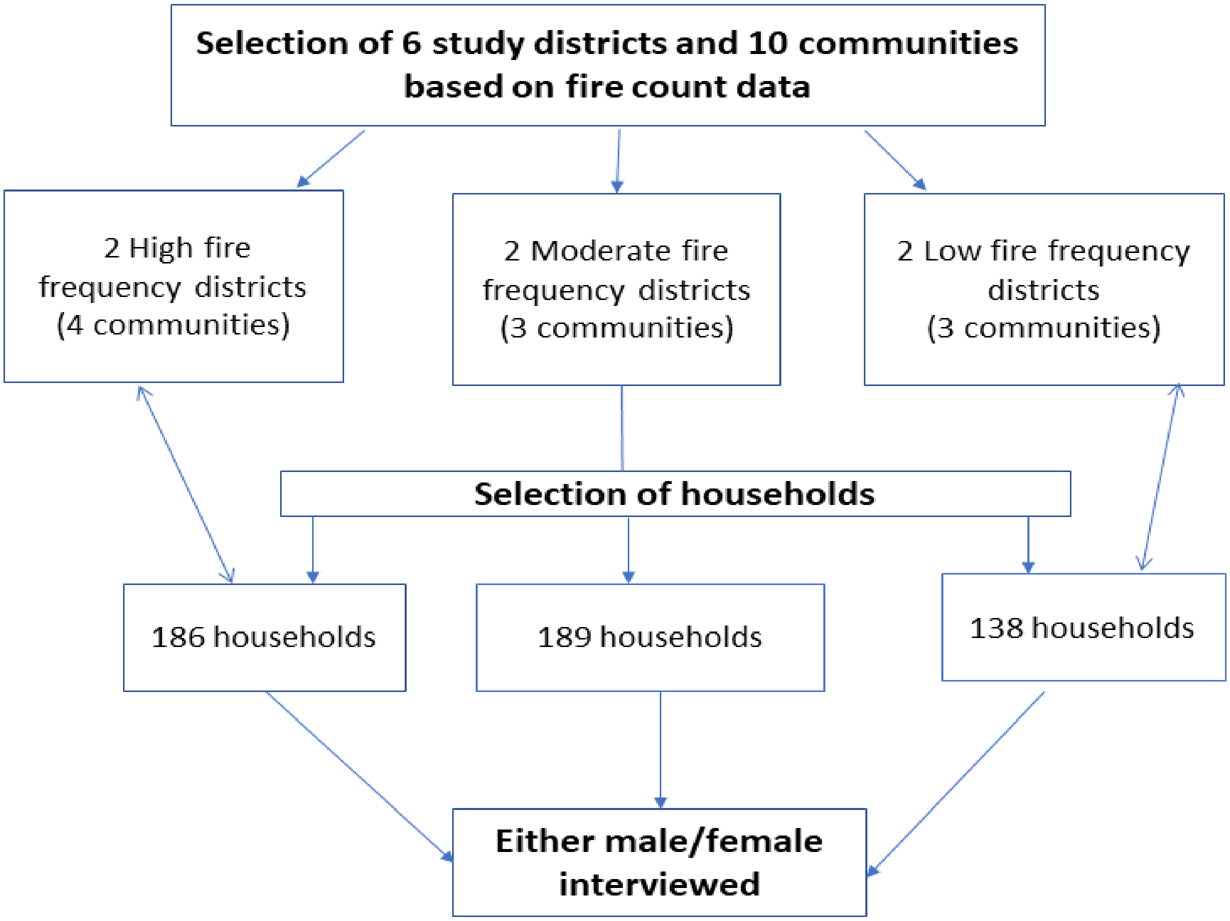


Figure 2. Selection of communities and households for the survey

Survey

A survey was conducted by using a questionnaire drafted in English. People were asked questions on their perceptions, practices and knowledge of the use of fire on selected livelihood activities. The questionnaire had three main sections: 1. Demographic characteristics. 2. Traditional fire practices, knowledge and perceptions of the use of fire, and 3. Fire regime and fire control practices. The questions were mostly closed-ended. The closed-ended questions were three-point (Jacoby and Matell 1971), and five-point Likert type questions, as well as binary type questions to indicate the importance and frequency of fire use (McDonald 2014). Participants were given options to explain their choice of answers to some of the questions, to aid in guiding responses and facilitating data coding. The questionnaire yielded mainly nominal, ordinal and a few continuous variables (age and household size).

The open-ended questions were used to ascertain the activities for which people use fire, people's practices and knowledge of the use of fire, the impacts of fire on the environment, as well as their knowledge of fire management. The activities (land preparation, hunting, firebreaks, bush clearing around homesteads, and burning stubble after harvest) were selected based on literature on fire use in savannas (Nyongesa and Vacik 2018).

The data were collected with the assistance of a research team selected from the University for Development Studies in Tamale, who are fluent speakers of the language spoken in the selected districts. The research team were all males and comprised of five assistants for East and West Gonja Districts, four for West Mamprusi and five for Tolon-Kubungu, Yendi and Tamale South districts. They were trained on the objectives and some terminologies of the study. By this the research team explained, agreed and translated some key concepts in the questionnaire into the various local dialects before going to the field.

We first met community leaders to seek permission and introduce the team by presenting kola nuts to the Chiefs or their representative at a brief meeting. We were permitted to engage with households with adults available because it was time for land preparation towards the farming season, thus some residents were not at home at most times of the interviews, so as we walked in the community, we select households with people available. However, either a male (mostly heads of households) or a female who was willing to answer the questions on fire use was interviewed in each of the communities.

Stern (2000) asserts that laws and government regulations are factors that may influence behaviours in responding to questions concerning themselves. Thus, we asked general questions on some sensitive items on hunting and charcoal making and sometimes probed further to get details. Data were collected from 11 March 2017 to 30 June 2017. The total number of responses was 532 of which 295 were from males and 237 from females. About 20-30 minutes was used for a questionnaire depending on how fast the respondent understood and responded to the items on the questionnaire.

Ethics statement

Formal ethics approval was not obtained because at the time of data collection in December 2016, the ethics form was still being developed by the Department. However, research ethics and protocols were observed. The research presents no risks of harm or no effects to the respondents, and involved no formal procedures for which written consents were required. But verbal consents were sought from the community leadership by following community entry protocols via communal meetings and presenting traditional gifts (e.g., kola nuts) to the chiefs, the assembly persons and other leaders in the communities. Some of these communities the research team (particularly the lead author) have worked for several years in different domains of research other than anthropogenic fires. We informed the community members that participation was voluntary, and should anyone feel uncomfortable with any of the questions they could discontinue answering the questionnaire without any negative consequences. We also informed the respondents and the leaders of the communities that the data will be analysed anonymously and all the information will be stored in a secure space where only the lead researchers and the supervisor have access. Participants were made to understand that the responses were for an academic purpose and I showed my Identity Card to the assembly persons as a proof of my status as a student. Participants were also assured of confidentiality. All the interviews were conducted in the local dialects of the selected districts as the majority of the respondents could not speak and understand English.

Data analysis

To provide an overview of socio-demographic characteristics, perceptions, knowledge and practices and respondents' use of fire, data were analysed using both descriptive and inferential statistics. Questions that yielded no and yes answers with reasons and some open-ended answers were classified into themes. All data were coded based on the commonalities in responses and data were entered, cleaned and analysed using SPSS Statistical Software Version 20.0. Some of the five-point Likert items were recoded into three-point items to allow more responses in the Likert items for statistical testing. Descriptive statistics were computed and a Chi-square test was used to examine for the presence of significant relationships and associations among variables across districts (McDonald, 2014). A Pearson's correlation between people's perceptions of fire effect on the environment and the frequency of fire use was also computed. In order to determine the relationship between fire use, socio-cultural practices and activities, multiple regression analyses were performed to examine how gender, occupation, district, age and ethnic group (which served as the independent variables) are correlated with fire use in the dry season, selected fire activities, reasons for fire use and fire control (as the dependent variables).

Results

Socio-demographic characteristics of respondents

The majority of respondents (79%) indicated they were farmers, 6% were students; and the remaining 15% engaged in other activities. Almost half of the of the respondents were female (45.5%) and 55.5% were male. The mean age of respondents was 39±15 years, with a minimum of 18 years and maximum age of 94 years. About a quarter of the respondents were between 26 and 32 years and the lowest (8%) were between of 47 and 53 years. The majority of respondents (66%) have no formal education and less than a quarter (15%) had education till Junior high school (JHS) or Middle school, and Senior High schools (SHS) (Table 1).

Table 1. Gender, age and educational distribution of respondents

Characteristic	Freq.(n)	%
Gender		
Male	295	55.5
Female	237	44.5
Total	532	100.0
Age (years) group		
18 - 25	93	17.5
26 - 32	112	21.1
33 - 39	107	19.9
40 - 46	94	17.7
47 - 53	42	7.9
54+	84	15.8
Education		
No formal education	347	65.5
Primary	46	8.7
JHS/Middle school	49	9.2
SHS	35	6.6
Tertiary	9	1.7
Non-formal	38	7.2
Other	6	1.1

The mean household size was 12.2±8 persons, with a minimum of one and maximum of 70 persons. The respondents comprised of people from nine ethnic groups: Dagomba (43%), Mamprusi (33%), Gonja (16%), Fulani (2%), Frafra (1%), Komkomba (2%), Dagaaba (1%), Buno (1%) and Mossi (1%).

Socio-demographic characteristics and fire use practices

The selected predictors in the regression analysis showed more significant relationships than other variables such as education, settlement status and household size. Thus, were excluded from the analyses. Significant, albeit weak relationships were found between fire use in the dry season and gender, age, ethnic group, occupation and district at $R^2 = 0.080$, $F_{(5, 370)} = 6.35$, $p < 0.0001$. Three out of the five variables: district ($p < 0.001$), gender ($p = 0.007$) and occupation ($p < 0.05$) added significantly to fire use in the dry season. The highest contributing variable was district (0.214). Districts were categorised into low, moderate and high in relation to the fire count data that informed the selection of the districts, thus it is to be expected that this variable contributed most to the model. Gender (0.138) also contributed to the model with mean having a high likelihood of using fire in the dry season than females. Occupation (0.102) also contributed, with 79% respondents who indicated farming as their occupation (Table 1). Age and ethnic group did were not statistically significant (Table 2).

There was a weak significant relationship across demographic groups in terms of the different activities for which fire was used at $R^2 = 0.043$, $F_{(5, 498)} = 5.43$, $p < 0.0001$. Of the five variables, age ($p < 0.0001$) and occupation ($p = 0.002$) added significantly to the use of fire for the selected activities in the region. Age as the highest predictor, contributed 0.180 while occupation contributed 0.144 to predict fire use for the selected activities. There were more people (79%) in farming than other occupations in this study. The remaining 15% in occupation including gari processing and only 6% were students (Table 1). About 80% of the farmers are within the age brackets of 20 and 70 years with less than 20% below the age of 20. District contributed negatively (-0.071) to the model, while gender and ethnic group were not significant.

It was important to find out how the selected independent variables were correlated with people's reasons for fire use. The results were significant at $R^2 = 0.085$, $F_{(5, 339)} = 6.23$, $p < 0.0001$. Three out of the five variables, namely ethnic group ($p < 0.001$), occupation ($p = 0.009$) and district ($p = 0.044$) added significantly to the model explaining reasons for fire use in the region. The highest contributing predictor was ethnic group (0.188). For instance, a total of 191 respondents indicated their use of fire for land preparation as part of their farming practices, with more Dagomba (64%) using fire for this activity than the Mamprusi (51%) and Mossi (1%). For occupation (0.149), again there were more

Dagomba ethnic (40%) in farming than other ethnic groups such as the Fulani (4 %) and district (0.110). Gender (0.030) and age (-0.043) were not significant.

Although, occupation ($p = 0.047$) contributed to the model for reasons why people control fire for the selected activities, the remaining four variables (age, gender, ethnic group and district) predicted poorly to the model and was therefore not statistically significant (Table 2).

Table 2. Multiple regression coefficients for the relationships between fire use practices and activities with some socio-demographic variables

Variable	Unstandardized Coefficients	Standardized Coefficients		t	Sig.	R2	F-ratio	p	SEE	N
	B	Std. Error	Beta							
Fire is use in the dry season										
(Constant)	-1.237	1.105		-1.120	0.263	0.088	6.35	0.000	3.75	370
Gender	1.075	0.396	0.138	2.712	0.007**					
Age range	0.116	0.129	0.051	0.902	0.367					
Occupation	0.233	0.122	0.102	1.901	0.054*					
Ethnic group	0.191	0.111	0.095	1.716	0.087					
District	0.602	0.147	0.214	4.087	0.000***					
Fire use for selected activities										
(Constant)	0.94	0.093		10.159	0.000	0.043	4.44	0.001	0.037	498
Gender	-0.018	0.012	-0.071	-1.556	0.120					
Age range	0.040	0.034	0.053	1.191	0.234					
Occupation	0.040	0.011	0.180	3.759	0.000***					
Ethnic Group	0.032	0.011	0.144	3.040	0.002**					
District	0.004	0.010	0.017	0.359	0.720					
Reasons for the use of fire										
(Constant)	0.901	0.672		1.342	0.181	0.085	6.25	0.000	2.22	339
Gender	0.178	0.088	0.110	2.026	0.044*					
Age range	0.133	0.240	0.030	0.556	0.578					
Occupation	-0.056	0.079	-0.043	-0.710	0.478					
Ethnic group	0.195	0.074	0.149	2.646	0.009**					
District	0.216	0.066	0.188	3.252	0.001***					
Reasons for controlling fire										
(Constant)	2.196	0.326		6.735	0.000	0.025	1.8	0.108	1.09	361
Gender	-0.019	0.116	-0.009	-0.163	0.871					
Age range	-0.064	0.037	-0.099	-1.763	0.079					
Occupation	-0.071	0.035	-0.112	-1.995	0.047*					
Ethnic group	0.026	0.034	0.045	0.777	0.438					
District	-0.055	0.041	-0.073	-1.337	0.182					

***$p < 0.001$, **$p \le 0.01$, *$p \le 0.05$.

Frequency of fire use for selected activities

The majority of respondents (83%) indicated that they used fire for at least one of the selected activities: land preparation, weed/grass/pest control, burning stubble after harvest, bush clearing around homesteads, firebreaks, charcoal burning and hunting (Table 3). Less than a fifth (17%) of said that they do not use fire in these activities. There were varied responses on how often fire was used for the selected activities across the high, moderate and low fire frequency districts. There was a significant association ($\chi^2 = 39.5$, df = 9, $p < 0.001$) between fire frequency and land preparation for crop production amongst the three categorised districts. The majority of respondents in the high (86%), moderate (85%) and low (75%) fire frequency districts indicated they used fire once a year for land preparation, while only 8%, in both high and moderate and 2% in low fire frequency districts, used fire twice a year for land preparation (Table 3). On average, 14% of the respondents across the districts never used fire for land preparation.

There was a significant association between the frequency of fire used for weed control and the district ($\chi^2 = 66.6$, df = 9, $p < 0.001$). On average, 13% of the respondents used fire once a year for weed control, while the majority (77%) never used fire for this purpose (Table 3). A little over a fifth (21%) of the respondents in the high-frequency zone, 11% in the moderate zone and 6% in the low zone, used fire once a year for weed control. In contrast, 73%, 77% and 93% of respondents in the high, moderate and low fire frequency zones, respectively, never used fire for weed control.

The majority of respondents (79%) never used fire to burn stubble after harvest, while less than a fifth (15%) used fire once a year for this purpose. More than half of the respondents in the high (52%) and low fire districts indicated that they burn stubbles after harvest. There was a significant association of frequency of fire use for stubble burning and districts ($\chi^2 = 74.8$, df = 9, $p < 0.001$).

Bush clearing around homesteads also showed a strong association ($\chi2 = 50.3$ df = 9, $p < 0.001$) with district. However, 67% of the respondents never used fire for clearing around homesteads. Twenty percent and 13% of the respondents used fire once and twice a year, respectively across the districts. However, about half (46%) of respondents in high fire frequency districts and 9% respondents in low fire frequency district said they used fire once a year. Whereas 45% in high, 60% in moderate and 80% in low fire frequency districts never used fire for clearing around homesteads (Table 3).

Respondents' use of fire to create firebreaks showed a strong significant association ($\chi^2 = 50.3$, df = 9, $p < 0.001$) among the districts. On average, 70% of the respondents in the moderate and low fire districts never used fire for firebreaks. About three-quarters (70%) of the respondents in high fire districts, and a little over a quarter of respondents in moderate (27%), as well as low (28%) fire frequency districts used fire once a year for firebreaks.

Similarly, there was a significant association of fire used for hunting ($\chi^2 = 26.88$, df = 9, $p < 0.003$) across the study districts. The majority (84%) of the respondents across the districts never used fire for hunting, with 11% in the moderate and as low as 7% in the high, 6% in the low fire frequency districts used fire once a year (Table 3).

Table 3 Respondents' frequency of fire use for activities across the selected districts

Activity	Frequency of fire use	District fire frequency				χ2	p-value
		High n (%)	Moderate n (%)	Low n (%)	Pooled n (%)		
Land preparation	Twice a year	8 (8)	8 (5)	3 (2)	19 (4)	39.5	0.001
	Once a year	79 (86)	180 (85)	127 (75)	386 (82)		
	Never	5 (6)	22 (10)	20 (24)	67 (14)		
Weed/grass /pest control	Twice a year	4 (6)	33 (12)	1 (1)	36 (10)	66.6	0.001
	Once a year	8 (21)	32 (11)	8 (6)	47 (13)		
	Never	28 (73)	104 (77)	140 (93)	273 (77)		
Burning stubbles after harvest	Twice a year	4 (7)	17 (9)	1 (1)	22 (6)	74.8	0.001
	Once a year	24 (52)	17(9)	13 (9)	54 (15)		
	Never	23 (41)	129 (82)	137 (91)	289 (79)		
Bush clearing around homesteads	Twice a year	10 (9)	23 (10)	9 (11)	49 (13)	50.03	0.001
	Once a year	24 (46)	35 (31)	14 (9)	73 (20)		
	Never	23(45)	109 (59)	122 (80)	250 (67)		
Hunting	Twice a year	3 (8)	20 (12)	-	23 (6)	26.9	0.003
	Once a year	5(7)	8 (11)	9 (6)	32 (10)		
	Never	35(84)	124 (77)	139 (94)	298 (84)		
Firebreak	Twice a year	1 (1)	8 (3)	3 (2)	12 (3)	159.7	0.001
	Once a year	55 (70)	14 (27)	43 (28)	112 (29)		
	Never	22 (29)	67 (70)	110 (70)	266 (68)		
Charcoal making	Twice a year	16 (30)	24 (20)	14 (9)	54 (14)	68.0	0.001
	Once a year	22 (38)	8.5 (14)	12 (16)	63(16)		
	Never	19 (32)	124 (66)	116 (75)	266 (70)		

Fire control practice for selected activities

The majority of interviewees (72%) said they always controlled fire for land preparation. In contrast, the majority of respondents indicated they never controlled fire for the other selected activities (Table 4). Respondents who controlled fire and those who never controlled fire enumerated reasons for which fire used for the selected activities should be controlled. Thus, 62% of 532 mentioned that they control fire to prevent destruction to property, 29% said it was to prevent destruction to vegetation and wildlife, 6% mentioned to maintain soil fertility, and the remaining 3% indicated to prevent death or injury to humans.

There were significant associations between respondents' fire control practices and the selected activities across the three fire gradient districts ($\chi^2 = 61.4$, df = 9, $p < 0.001$). Around three-quarters (72%) of the respondents indicated that they controlled fire used for land preparation. Seventy-nine percent of the respondents in high fire frequency districts, and 74% for moderate and low (73%) indicated that they always controlled fire used for land preparation (Table 4). Less than a quarter across the district never controlled fire during land preparation.

Contrary to the control of fire for land preparation, 82% of the respondents in each of the districts never controlled fire used for weed control. Only a fifth of respondents in the high (10%) moderate (9%), and low (6%) fire frequency districts always controlled fire ($\chi^2 = 48.5$, df = 9, $p < 0.001$).

However, 59% of the respondents in the high fire frequency districts and less than a tenth of the respondents in the low (6%) and moderate (3%) fire districts, always controlled fire used for burning stubble. However, the majority (> 90%) of respondents in both moderate and low and the lowest 34% in high fire frequency districts never controlled fire used for burning stubble ($\chi^2 = 39.5$, df = 9, $p < 0.001$). As much as twice the number of respondents (65%) in high fire districts always controlled fire used for firebreaks than those in low fire frequency districts (31%), with only 6% in the moderate fire frequency districts ($\chi^2 = 159.7$, df = 9, $p < 0.001$).

The majority (90%) of respondents in all the districts indicated that they never controlled fire used for hunting, while less than a fifth of the respondents in the districts, controlled fire always (Table 4). However, respondents in the high fire (64%), low fire (23%) and moderate fire (16%) districts always controlled fire used for charcoal making (Table 4).

Table 4. Respondents' practice of fire control in socio-cultural fire use practices across the fire frequency districts.

Activity	Practice of fire control	District fire frequency				χ^2	p-value
		High n (%)	Moderate n (%)	Low n (%)	Pooled n (%)		
Land preparation	Always	75 (79)	125 (74)	121 (73)	321 (72)	61.4	0.001
	Sometimes	12 (14)	15 (12)	10 (6)	57 (13)		
	Never	6 (7)	30 (15)	34 (21)	70 (16)		
Weed//pest control	Always	12 (15)	19 (9)	8 (6)	26 (8)	48.5	0.001
	Sometimes	8 (10)	18 (8)	1 (1)	29 (9)		
	Never	7 (6)	108 (83)	132 (93)	274 (83)		
Burning stubbles after harvest	Always	17 (59)	4 (3)	9 (7)	30 (9)	126.7	0.001
	Sometimes	6 (7)	5 (3)	4 (3)	15 (5)		
	Never	28 (34)	128 (95)	129 (91)	285 (86)		
Bush clearing around homesteads	Always	29 (65)	30 (18)	28 (20)	87 (25)	78.6	0.001
	Sometimes	6 (8)	7 (35)	1 (1)	15 (5)		
	Never	22 (28)	105 (79)	114 (79)	241 (70)		
Hunting	Always	9 (20)	5 (2)	6 (5)	20 (6)	67.4	0.001
	Sometimes	2 (5)	10 (5)	2 (1)	14 (4)		
	Never	32 (75)	131 (93)	130 (94)	293 (90)		
Firebreak	Always	42 (65)	5 (6)	45 (31)	92 (27)	171.9	0.001
	Sometimes	3 (4)	1 (1)	1 (1)	6 (2)		
	Never	25 (31)	115 (92)	104 (68)	244 (71)		
Charcoal making	Always	34 (64)	21 (16)	33 (23)	88 (24)	102.7	0.001
	Sometimes	4 (6)	12 (5)	1 (1)	17 (5)		
	Never	24 (29)	119 (79)	110 (76)	254 (71)		

Perceptions of the importance of fire regimes

There were varied perceptions of fire regimes. There was evidence of significant relationships in the perceptions of fire regimes with fire frequency districts (Table 5). Half of the respondents (50%) in the high, 43% in the low and 33% in the moderate fire frequency districts, were of the opinion that the season of burning was very important. While less than a fifth in each of the districts said the season of burning was not important.

The majority of respondents perceived the severity of fire as important but not very important: 45%, 41% and 28% in high, moderate and low districts, respectively, indicated that the severity of fire was important. However, more than half of the respondents (53%) in the low fire districts and less than half of the respondents in moderate (43%) and high (33%) fire frequency districts indicated that, the severity of fire was not important

About 59% of the respondents perceived that the frequency of burn was unimportant. However, 33% in moderate, 30% in high and 17% low fire frequency districts showed the frequency of burning was important. Similar to the responses on perceptions of fire frequency, on average the respondents (58%) in each of the districts were of the opinion that the type of fire was unimportant. Thus, less than a quarter of the number of respondents in each of the districts thought the type of fire was very important (Table 5).

Table 5. Respondents' perceptions of the importance of fire regimes across the six fire districts

Fire attribute	Importance of fire attributes	District fire frequency				χ2	p-value
		High n (%)	Moderate n (%)	Low n (%)	Pooled n (%)		
Season of burning (timing; dry, season, early or late)	Very Important	46 (50)	49(33)	90 (53)	185 (43)	55.6	0.001
	Important	28 (32)	95(51)	49 (29)	173 (40)		
	Not important	20 (18)	23 (15)	30 (18)	73 (17)		
Severity of fire (what is burnt, soil vegetation mortality, high, moderate, low)	Very Important	21(21)	28 (17)	30 (18)	79 (18)	40.8	0.001
	Important	37(45)	68 (41)	47 (28)	152 (36)		
	Not important	33 (34)	75 (43)	8 (53)	196 (46)		
Frequency of fire (fire return interval and number of ignitions)	Very Important	14 (18)	11 (5)	24(15)	49 (12)	53.8	0.001
	Important	28 (30)	62 (33)	27(17)	117 (29)		
	Not important	47 (52)	79 (63)	112 (69)	238 (59)		
Type of fire (size and pattern)	Very Important	20 (22)	16 (7)	19 (12)	55 (13)	37.7	0.001
	Important	20 (22)	62 (29)	38 (23)	120 (29)		
	Not important	48 (56)	85(63)	105 (65)	240 (58)		

Respondents' perceptions of the effects of fire on the environment and the frequency of fire use

About 77% of the respondents were of the view that fire was not good for the environment, 8% thought fire use was good for the environment while the remaining 14% indicated they did not know. However, 35%of the respondents who indicated that burning was good for the environment, perceived that burning increased soil fertility, followed by 28% thought that it improved crop yields, while less than 1% said it was good for hunting (Figure 3). In contrast, 42% of the respondents who said that burning was not good, were of the view that fire destroyed vegetation, and 33% felt that fire decreased soil fertility (Figure 3 A and B).

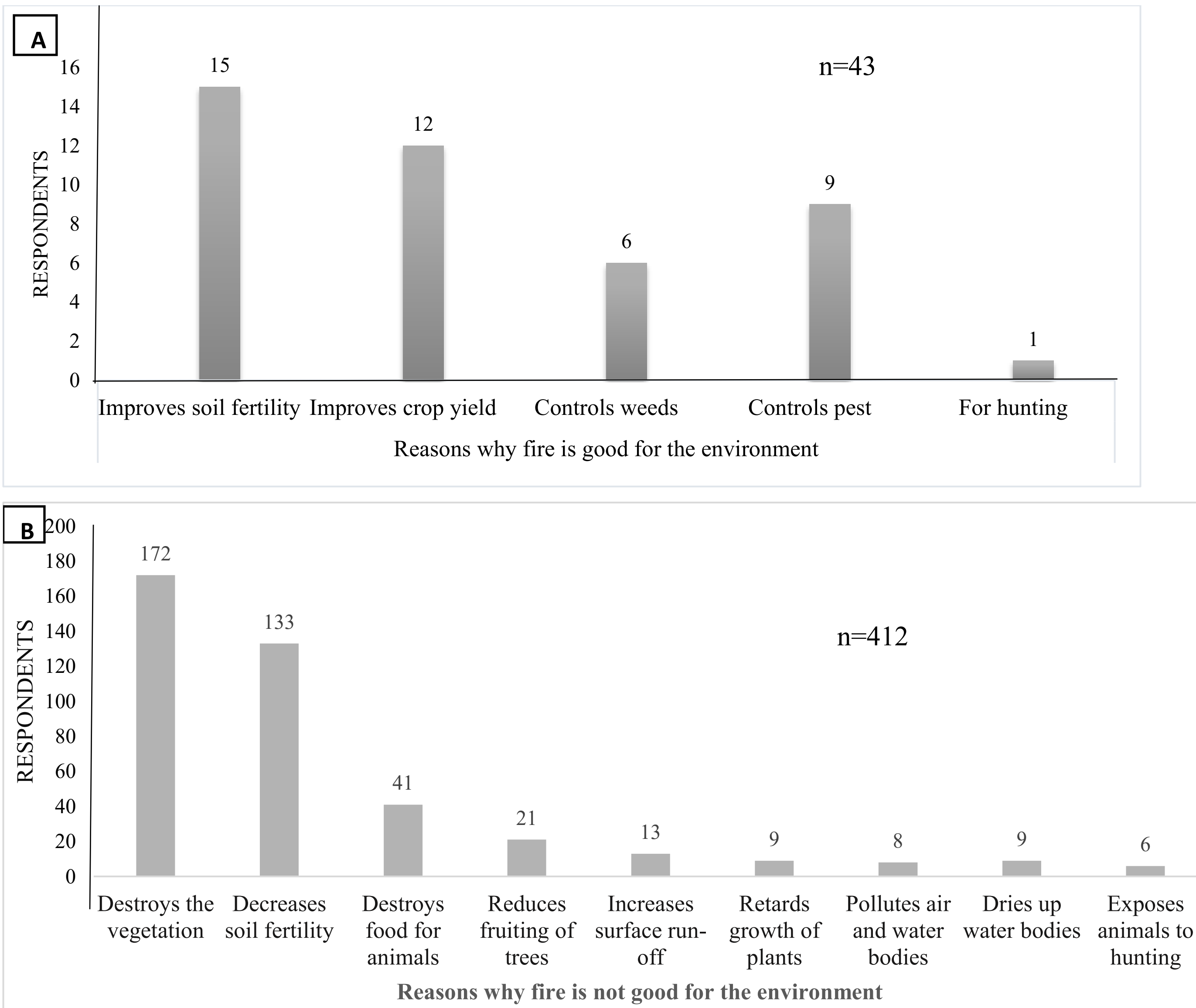


Figure 3 - Respondents' opinions on **A** – positive effect of fire and B - negative effects of fire on the environment.

Discussion

Socio-demographic characteristics and fire use practices

The five predictor variables (gender, age, ethnic group, occupation and district) with fire use in the dry season indicate that fire incidences around this time of the year is purposeful and that it is associated to reasons for fire occurrence in most rural savanna regions of Ghana. Thus, seasonality determines fire occurrence, which is also dependent on livelihood (occupation) and some cultural activities in rural savannas of Africa (Eriksen 2007; Archibald 2016). This has also been found in fire prone areas around the world. For instance, William (2002) listed activities carried out by native Americans during particular seasons of the year. The list of activities (e.g., clear agricultural fields and replenish the soil from the ash) in William (2002) aligns with Nyongesa and Vacik's (2018) study in Kenya, Laris et al. (2011) in Mali as well as results in this study. Also, the Maori's of New Zealand primarily use fire for hunting game and clearing land for cropping (Baillie and Bayne 2000), which were also identified in this study. Thus, the season for fire use is strongly related to the major occupation (farming in this case) of the people, ethnicity and location as found in the regression analysis.

There is an influence of location (districts) and ethnicity on fire activities in the dry season. This study stipulates that high fire frequency districts fall within areas with dense vegetation during the rainy season, which results in a build-up fuel during the dry season. Thus, people burn as they see drier grass cover during the dry season (Archibald 2016). Districts with low fire frequency on the other hand, are characterised by sparse vegetation and more buildings than high fire frequency sites (Amoako and Gambiza 2019). It is also noted that most of the respondents are indigenes of the various districts, hence corresponding to their occupation and activities which are land-based, with a few who have migrated from other districts mainly for farming. The access to land for farming through customary arrangements is very lenient in this part of Ghana (Tomomatsu 2014). Thus, land is transferred from one generation to the other, the same way as traditional practices and knowledge of fire use has been transferred over the years (Shaffer 2010). In rural Africa and Ghana for that matter, ethnicity can be linked to the location, as the Dagomba is the dominant ethnic group not only in this study but in the Northern region of Ghana (Ghana Statistical Service 2010; Tomomatsu 2014). The Dagomba ethnic group do not occupy the largest land area but were found in most of the communities particularly in the East and West Gonja (high fire frequency) districts but whose indigenes are the Gonja ethnic group. Ethnicity, however, did not make any significant prediction to the reason for the use of fire, indicating that all the ethnic groups have similar reasons for the use of fire, especially for land preparation for cropping which is the major reasons for fire use across all the districts.

As observed in the model, gender plays a role in fire activities. This is not surprising, because most of both men and women indicated farming as their major occupation. The women, however, specified that they were also engaged in other livelihood activities such as shea fruit picking and charcoal making which involve the use of fire. This is supported by anecdotal reports of fire use in parklands by women, to reduce the grass cover for easy picking of shea fruits and wood fuel (mainly a woman's role), as well as protection against harmful reptiles while engaged in these activities. Women may not be directly involved in the use of fire for some socio-economic and cultural practices such land preparation, hunting and clearing around homesteads due to the specificality of gender roles in these activities in rural areas (Eriksen and Hankin 2015).

Although the peak for fire use is the dry season for selected activities, the use of fire by women may be negligible during this period as major livelihood activities of women are in the dry season. For instance, fire use for land preparation in this study comes as the biggest fire activity, meanwhile in the Northern savanna zones of Ghana, land preparation for cropping is a preserve for men. Women do the planting and harvesting of crops as practiced in most parts of Africa (Longhurst 1985). Thus, gender makes a statistically significant difference in the season and reason for fire use as observed in the analyses. In this vein, Campbell and Bell (2000) argue that the way rural men conduct their lives has an enormous impact on how rural women live their lives. However, Villamor et al. (2013), using examples from Indonesia, assert that women's involvement in environmental management decisions as a whole has changed for good, over time and must be applauded. So that gender really matters when it comes to fire use and management in rural areas (Eriksen and Hankin 2015). Since the effects of fires on the parklands of West Africa affect livelihoods of both men and women, the inclusion of men and women in the conservation of savannas is necessary.

The season and reasons for fire use and control of fires are mostly for livelihood purposes which are linked to occupation as observed in this study. The results support the argument that humans have influenced fire regimes around the world, including the African continent and West Africa specifically (Archibald 2016; N'dri et al. 2018). It is important to mention that people's practices, knowledge and perceptions in turn influence the reason and season of burn and the frequency of fires in particular. In the Guinea savanna of West Africa for instance, occupation drives the use of fire, which over time, impacts on vegetation, soils and other aspects of the environment at the local level, and the sub-Saharan regional level (Eriksen 2007; Dwomoh and Wimberly 2017).

Frequency of fire use for selected activities across the districts

The frequency of fire use is an important attribute of fire regimes which is characterised by the fire return interval and the number of fires that occur within a given period of time. Most of the respondents were involved in farming as their occupation, hence, the high response rate for using fire once a year for land preparation. This supports Ramo et al.'s (2020) findings of frequent and high fire use on croplands in African savannas. The response for fire use once a year corresponds with the unimodal rainy season and the long dry season (up to six months) in the study area. Studies have shown that crop farmers in the West African savannas, burn to reduce trash and get rid of the grass and other herbaceous vegetation from the previous growing season. The burning is done for easy hoeing or ploughing of the land for the next cropping (Amissah et al. 2010; Shaffer 2010). The respondents who indicated that they used fire twice a year for land preparation, may do this on occasions where they have to clear a new place for cropping; the first burning is to clear the bush, then fire is used again to remove stumps of the large woody species as observed by Eastmond and Faust (2006) and during the field reconnaissance survey for this study.

The high fire frequency districts are located in a closed savanna (Bagamsah 2005) that is characterised dominated by tall grasses and relatively good soil for agricultural production. As a result, even people in the low fire areas, particularly those that are 'urbanised', move to these areas for farming using traditional agricultural practices, which could also contribute to high fire frequency. High grass growth during the rainy season enhances the fuel load in the dry season. This results in high intensity fires with burning temperatures between 791°C as observed by Kugbe et al. (2014) in the study area. Veenendaal et al. (2018) also observed that fire return intervals are largest for tall savanna woodlands and dry forests. Thus, there is a possibility that fires in these areas may increase as conditions (heavy rainfall that promotes good grass growth and the hash Harmattan conditions) for fire ignition become more conducive (Amoako et al. 2018). Population growth in urban areas and high cost of tractor services for land preparation, and the resultant high demand for pulses, cereals and yam grown in the agroforestry parklands (where smallholder farmers still use traditional methods of farming involving the use of fire) could also increase the use of fire for land preparation in West African savannas.

According to Nyongesa and Vacik (2018), the use of fire for weed control is another cultural practice amongst rural dwellers in most African savannas. Some respondents indicated that they used fire for weed control, including the control of *Striga hermonthica*. This was also observed in Kenya, where farmers indicated burning and hand weeding to control *Striga hermonthica* on crop fields (Atera et al. 2018). Other studies (DiTomaso and Johnson 2006; Morton et al. 2010; Mckell et al. 2015), have also reported that the use of prescribed fires (also referred to as flame weeding) to control recalcitrant pests, weeds and invasive species such as *Centauries solstitialis* (Yellow star-thistle) in California (DiTomaso and Johnson 2006). Prescribed fire use in Ngorongoro, Kenya, was also successful in the control of ticks (Fyumagwa et al. 2007). However, the use of weedicides and herbicides is probably gaining ground because of their ready availability in local markets even in remote areas of Ghana (Nkansah 2014). Some respondents explained that it is difficult to apply fire while crops are still in the field and would prefer to use chemicals and rather burn for land preparation. This could also be the reason for the relatively high responses for fire use after harvesting for burning stubble, which sometimes forms part of the process of land preparation and crop production (Chan and Heenan 2005).

Studies (Shaffer 2010; Nyongesa and Vacik 2018) have shown that the use of fire for clearing bush around homesteads during the dry season is a common practice in rural communities in Africa. Most of the study districts are rural with homes having bushy surroundings which dry out during the every Harmattan season. As a result, applying fire is much cheaper and more practical than weeding or applying weedicides, as explained by some of the respondents. In contrast, the districts in urban areas with high human populations have more paved surroundings, thus little use of fire for this activity has been observed (Archibald 2016). Nyongesa and Vacik (2018) also have shown that the use of fire in crop fields is to save on labour and the cost of chemicals.

Homesteads are mostly used for compound gardens in the rainy season to supply vegetables to supplement the nutritional needs of the household. These supplementary farms are known as compound farms which are burnt to get rid of the dried stubble in time for the next rainy season.

Burning around homesteads is also done to get rid of ticks and reptiles as these homesteads contain stables for cattle and other livestock (Mistry et al. 2016). The practice of using fire for creating firebreaks was relatively high across the study areas. This confirms the findings of Shaffer (2010) and Nyongesa and Vacik (2018), who observed in Mozambique and Kenya, respectively, that using fire for firebreaks was done to reduce fire risks within the communities and to protect livestock as well as crops which are yet to be harvested.

Questions on hunting and charcoal burning appeared to be quite sensitive particularly in communities with government protected forests but had vast areas burnt, either due to uncontrolled fires from hunting or poaching, as well as charcoal production (Agyeman et al. 2012; Walters 2012; Abukari and Mwalyosi 2018). Because some people felt reluctant to indicate their use of fire for these activities, we made them to understand that the questionnaire was for study purpose. Aside from responses for questions regarding charcoal burning and hunting across the districts, anecdotal evidence, satellite observations (SERVIR West Africa, 2019) and field observations during data collection revealed that there is a high use of fire for charcoal production and hunting. We also observed a lot of on-going charcoal production in some of the communities. The respondents' reluctance in giving honest answers on their use of fire for charcoal production and hunting could be attributed to people's awareness of the dangers and adverse effects that these activities have on the environment, human lives and property. Also, there has been a radio campaign against these practices, as well as local announcements made by traditional authorities at the beginning of every dry season (Amoako et al. 2015).

Additionally, the respondents seem to be aware of the suggested policy ban on charcoal production and so some of the respondents would not indicate that they used fire for charcoal burning. It is not surprising that people's perception and the frequency of fire use for this activity showed a negative correlation. We realised that although people were aware of the effects of fire on the environment, they still produce charcoal, which has become an alternative source of livelihood income in the dry season in recent times due to the unpredictable rainfall and crop failure. Agyeman et al. (2012) suggested that instead of placing a ban on charcoal, which is a lucrative source of livelihood income for rural people in the savannas of Ghana, the government should put in place measures to sustain the charcoal industry. However, Msuya et al. (2011) argued that efforts should be made to reduce and prohibit the use of charcoal in cities and towns in order to reduce the degradation and its attendant effects on the savanna and forests in Africa.

Fire control practice

The practice of fire control for the selected activities refers to the use of fire with caution and supervision to achieve the desired results. Shaffer (2010) indicated that fires that are deliberately ignited for livelihood activities are usually controlled. Bowman et al. (2008) also found that traditional households that use fire in the Brazilian Amazon were actively engaged in fire management to protect their properties and farmlands.

It was observed that the high fire frequency districts had the highest responses for the use of fire once a year for almost all the selected activities. The respondents also exhibited more knowledge and practice of fire control for all the activities than those in moderate and low fire frequency districts who never tried to controlled fire. However, this may not necessarily mean that those who never control fires are not aware of the control measures, but may use less fire hence; there is little need for fire control.

The high proportion of respondents who control fire for the selected activities in the high fire frequency districts is an indication that the people were aware of the need to control fires to prevent destruction to humans, wildlife and property. This was observed in studies in Brazil (Bowman et al. 2008) and Kenya (Nyongesa and Vacik 2018) where fires applied intentionally, are always controlled. In Burkina Faso, fire control practice is embedded in fire management plans and practices, which has proven successful in fire use for agriculture and customary burning (Mäkelä and Hermunen 2007).

Perceptions of the importance of fire regimes and the knowledge of fire effects on the environment

It was noted that fire regimes in the Guinea savanna are characterised by land use patterns and practices linked to livelihood and socio-cultural activities, and which are in turn determined by the season of burning, severity, frequency and size. The season of burning was rated very important, which confirms why most burning is done in the dry season to prepare farm lands for cropping in the rainy season (Veenendaal et al. 2018). This finding agrees with other studies which found vegetation burning in other tropical savannas (Mistry, 1998) to occur mostly in the dry season; the active fire season in the Sudano Guinean savanna (Rose Innes 1972; Dwomoh and Wimberly 2017; Laris et al. 2017). The same studies (Rose Innes 1972; Dwomoh and Wimberly 2017; Laris et al. 2017) reported that most of the fires are caused by humans for the activities mentioned in this study and other studies (Archibald 2016; Dwomoh and Wimberly 2017). Our observation during a reconnaissance survey was that most burning was done during December and January (early dry season) with a reduction in the number of fire occurrences towards the mid (February) and late dry season (March-April). Respondents' explanations indicated that burning is, however, dependent on the time the rains end (drought sets in). Thus, the timing and severity of drought within the dry season are fire conditions that play a major role in the fire regimes of the Guinea savanna.

Most respondents indicated that fire could be devastating to all aspects of the environment, (including pollution of water bodies contributing to soil erosion) if not controlled; however, they attached more importance to the season of burning over the intensity of the fire. For instance, Laris et al. (2017) also placed more emphasis on the season of burning than severity. The authors attributed the season of burning as a determinant of intensity and severity. Nonetheless these attributes are characterised by the extent of drought, which influences fuel load, moisture content and local conditions (land use patterns and practices) and vary from place to place in the Guinean savanna of West Africa. Gambiza et al. (2005) and Govender et al. (2006) also observed in Southern Africa that fire severity is determined by the season of burning which is also influenced by factors including the moisture content, fuel load and fuel characteristics. A recent study by N'Dri et al. (2018) on fire behaviour in the Guinea savanna of Ivory Coast, confirmed that the severity and intensity of fire is influenced by season of burning. The study also indicated that the rate of spread and intensity of fires increased with the length of the dry season.

However, most of the respondents did not see the link between the season of burning and the severity of fire. Although the respondents indicated that they burnt earlier in the dry season when the vegetation is not too dry, they rated severity of fire as not important. This suggests a knowledge gap in respondents understanding of the concept of fire regime. This confirms Huffman's (2013) findings that people had limited understanding on how some fire attributes interrelate and influence one another. This supports Rodríguez-Trejo et al. (2011) recommendations that the results of scientific research on the concept of fire regimes should be merged with traditional fire knowledge for long term integrated fire management.

Fire frequency was rated as unimportant by respondents. Contrarily, there was, however, a strong positive correlation between fire effect on the environment and how often people used fire for land preparation. the majority of respondents did not perceive fire return intervals and number of ignitions as a problem. Minnich et al. (1993) argued that human-caused fire frequency (number of ignitions) is unimportant, because the onset of natural fires could have more devastating affects since natural fires occur when there is much fuel load for burning. This can result in high intensity fires than frequent human-ignited fires. However, Griffiths et al. (2015) found that fire frequency has an enormous effect on both plant and animal species, and therefore should not be underestimated.

Most respondents thought the type of fire which encompasses pattern and size of fire was unimportant. However, Govender et al. (2006), have shown that fire severity is influenced by the type of fire which is in turn affected by the season of fire. This suggests the need to address the knowledge gap in managing the traditional uses of fire and fire regimes in different savanna regions in Africa.

As shown in this and other studies, most fires in these savannas occur annually and at specific times, which has defined the anthropogenic fire regimes in these savannas (Devineau 2010; Archibald 2016). There is a need for further studies to understand the complexities of human-driven fire regimes in African savannas where season and frequency of fires are the seemingly recognisable components of fire regime by traditional fire users as shown in this and other studies (Nyongesa and Vacik 2018, Archibald 2016; Archibald et al. 2012; Kugbe et al. 2012, 2014). The other components (type, behaviour, intensity, severity) of a fire regime have received low recognition in traditional fire knowledge management (Huffman 2013). Thus, Archibald (2012) asserted that the season of burning or the conditions of combustion and type of vegetation burnt could be complex, hence misinterpreted as a change in fire frequency and vice versa.

Conclusion

The study confirms that the use of fire for agriculture and some socio-cultural purposes is a characteristic of traditional livelihood practices, but could have enormous impacts on the environment, as outlined by the respondents. Most of the respondents are farmers who use fire annually for land preparation for cropping. This was confirmed through the predictors with each of the response variables. The high fire frequency districts used fire for almost all the selected activities, thereby increasing the fire occurrences in these districts. This confirms the findings in fire count data obtained from the CSIR Meraka Institute.

The study revealed that fires that are set on purpose were mostly controlled, particularly for land preparation for cropping, which indicates people's awareness of the hazards associated with uncontrolled fires. There's the need to study the ecological effects of traditional fire use through the integration of historical and current human fire use ecology. This will facilitate a transdisciplinary approach to fire rural fire management.

The season of burning was rated as a very important component of fire regimes. The respondents' stated that early and late season burning was dependent on the time the drought sets in. Notwithstanding, the type of fire was the least rated amongst the four attributes of a fire regime. More awareness on the impacts of different fire regimes could improve fire management in fire-prone areas. Most respondents were aware of the adverse effects of fire on the environment. This positive knowledge base could also be a foundation for the education and training in good fire management practices in the rural communities of West Africa.

The former fire volunteer squads in some communities should be retrained and replicated by district assemblies to assist in the management of fires for agricultural purposes as well as other socio-cultural practices within rural areas in the north of Ghana where fire use is common. Collaborative sharing and learning of traditional ecological fire knowledge management between regional, district directorates of Ministry of Food and Agriculture, the Forestry Commission, the Environmental Protection Authority, Environmental NGOs and researchers is important in the management of the savannas of the Guinea savanna and West Africa at large.

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CHAPTER 3: THE EFFECTS OF TIME OF BURNING ON TREE SPECIES COMPOSITION IN THE GUINEA SAVANNA

Abstract

Biomass burning is a common practice in the Guinea savanna of Ghana. Burning begins at the onset of the dry season (November) and lasts until the end (April) of the season. This study investigated the effects of time of burning on tree diversity and density in the Mole National Park, Ghana. A total of 36 quadrats (10 m by 10 m) were systematically sampled in a 200 m by 200 m treatment plot each for early, late dry season burning and no-burning plots. Twenty-seven different woody species belonging to fourteen families were recorded in all the treatments. Most of the species identified belonged to the families Combretaceae and Fabaceae. *Vitellaria paradoxa*, *Terminalia avicennioides*, *Combretum adenogonium* and *Combretum molle* were the most common and abundant in all treatments. The late burn and no-burn treatments recorded the lowest diversity amongst the three treatments. The no-burn treatment had higher tree density than both burnt treatments. Early burning treatment had a higher diversity but the lowest density compared to the late burning treatment. Sustainable land use practices including protection of trees on farms and prescribed early dry season burns could contribute to the management of indigenous woody species in fire prone savanna as the Guinea savanna.

Keywords: burning time, Guinea savanna, Mole National Park, woody species

Introduction

Savannas are known to support a large number of plant communities and the species therein (Scholes and Walker 1993; Osborne et al. 2018). However, natural and human disturbances are considered major drivers of species occurrence and diversity in savannas. The frequency and magnitude of disturbances are major factors shaping savannas (Sheuyange et al. 2005; Andersen et al. 2012), and amongst these, natural and anthropogenic fires are important in savanna ecosystem function. However, fire regimes have been increasingly altered by human use of fire for various fire-assisted activities (Sheuyange et al. 2005; Santin and Doerr 2016; Osborne et al. 2018). Thus, fire is recognised as a tool in traditional fire practices in many rural economies, as well as the management of vegetation in conservation sites around the world (Eriksen 2007; Archibald 2016; Beale et al. 2018).

African savannas in particular, have been influenced by fire and adapted to it over millenia (Beringer et al. 2007; van Wilgen 2009). Thus, to a large extent, many species in African savannas have adapted different mechanisms to survive persistent fires, which include developing fire-resistant bark, roots that grow deep into the ground and growing dormant buds (Nefabus and Gambiza 2007). Some researchers recognise that anthropogenic fires play a vital ecological role in the occurrence, evolution and conservation of productive and resilient savannas (Archibald 2012; Andela & van der Werf 2014; Andela et al. 2017).

Many rural dwellers in savannas around the world use fire for cultural, social and economic purposes. For instance, in Kenya, other parts of Africa (Nyongesa and Vacik 2018) and Brazil (Mistry 1998; Miranda et al. 2002), fire is used to stimulate the growth of fresh forage for animals, for tapping honey and attracting game for hunting. In Ghana, fire is also used to minimise labour costs in land preparation as well as increase agricultural production and productivity (Amoako et al. 2018). In savanna conservation sites and protected areas, including the Serengeti, Tanzania, fire is used to control vegetation so as to keep it open for grazing animals. In the Kruger National Park, South Africa, fire is applied to reduce wildfire risk later in the fire season, which is the same practice in the Mole National Park, Ghana (Beale et al. 2018). Still in South Africa, the management of the Pilanesberg National Park believes that fire diversity supports biodiversity (Beale et al. 2018). Other studies have also indicated that frequent burning resulted in patch mosaics of vegetation, exhibiting diverse stages of recovery at the landscape scale but could result in changes in vegetation cover, species richness and composition at the regional and subsequently at a global scale (Gomes et al. 2020). For the reasons mentioned above, Alvarado et al. (2018) asserted that fire suppression in fire prone savannas may not change the area burnt, but rather make fewer and bigger fires with less diversity.

In spite of the myriad practical fire uses, the general attitude and perceptions regarding its use has often been negative, a legacy of colonial restrictions but fires are not perceived as harmful by local communities. Annual burning is alleged to affect the savanna vegetation and also some land-based livelihoods of local people (Eriksen 2007; Adongo et al. 2012). Although fires rarely kill large trees, many other life forms can be significantly affected (Gill 2005). Saplings and some grass species may be eliminated as a result (Lykke 1998; Gill 2005). Some studies have shown that ecosystem degradation by fire reduces carbon sequestration and thus may turn carbon sinks into emission sources thereby exacerbating the impacts of climate change in the region and at the global level (Thonicke et al. 2000; Andersen et al. 2012).

Fires are known to break the dormancy of some plant species which enhances recruitment and adaptability to fire-prone environments (Auld and Bradstock, 1996). In Kenya fire is also reported to be effective in the elimination of competing and parasitic species such as *Striga hermonthica*, and improving habitats (Denslow 2002; Atera et al. 2018). Gomes et al. (2020) observed that in the Brazilian Cerrado, for instance, biennial fires increased the recovery of herbaceous biomass from 40% to 60%, 24 months after fire. Ruthven et al. (2003) on the other hand, observed in Texas that frequent use of fire eliminated less fire-tolerant woody and grass species. Gill (2005) showed that late season fires may be detrimental to some plant species and cause the extinction of other species. Sheunyange et al. (2005) argued that frequent fires reduced shrub species richness, but positively influenced tree species richness in Namibia.

As discussed in the conceptual framing of this thesis on fire regimes (Chapter 1), fires have differential effects on savanna landscapes depending on the fire regime, which is in turn influenced by factors such climate, soil and plant type (Sheuyange et al. 2005). Fires have shown to have both depressive and stimulatory effects depending on the intensity, frequency, season (including the time of burning: early or late within the season) and type of species (Birnin-Yauri and Aliero 2010).

However, season is a primary predictor of fire ignitions, hence it affects the other attributes of a fire regime (Archibald et al. 2012; Alvarado et al. 2018). Chapter 2 of this study also confirms that people are more concerned about the season of fire than frequency and type of fire. Certainly, the time of ignition of fire during the long dry season in most savannas has ecological implications, particularly on plant species over space and time, although, Fontain et al. (2009) and Russels et al. (2003) have shown that in Australia, the frequency at which the vegetation is burnt determines the species that dominate a plant community, but not the time of burning. William et al. (1998) on the other hand, found that late season fires were devasting, primarily because there was more dry fuel with extreme fire weather. The study further showed that different plant species responded to fire differently.

The different times of fire application within the fire season may favour the growth of different plant species. Similar to some mature plants, some seeds have fire adaptive traits to late season fires that stimulate germination and succession after fire (Gomes et al. 2020), thus, increasing their germination percentage and abundance (Gomes 2020). In contrast, Myers et al. (2004) and Penman et al. (2007) have shown that some seeds are not able to withstand fires but gradually disappear. However, in the Guinea savanna of Ivory Coast, N'dri et al. (2018) found that mid and late season fires did not have significant damaging effect on trees because most trees shed their leaves before the late season, opposing the observations by Williams et al. (1998) in Australia. Whereas the effects of fire on plant communities and species have received extensive attention, the significance of altered species due to the specific attributes of a fire regime are poorly investigated.

In this regard, the role of time within the season and frequency of burning or no-burning and their effect on species composition in terms of frequency and diversity in savanna ecosystem management is important. Although fire seems to be an indispensable tool for managing savannas, the influence of fire on plant species density and diversity in the Sudano-Guinean savanna needs to be studied further. There are very few studies conducted on how the time of burning influences species composition in the Guinean savanna (Brookman-Amissah et al. 1980; Bagamsah 2005). Again, with the changing climate and fire conditions over time and space there's the need to keep track of species composition in fire prone savannas.

The Northern Region of Ghana contains about 50% of the Guinea savanna of the country and has recorded higher occurrences of fires (40-60%) in the last 30-40 years, than the other regions

(Amanor 2002; Kugbe et al. 2012). The frequent and uncontrolled fires may influence plant species composition and densities differently in the already sparsely populated parkland (Russels et al. 2003; Fontain et al. 2009; Andersen and Williams 2012). This study, therefore, was conducted to investigate the effects of the time of burning on woody species composition and diversity. I hypothesised that the time and season of burning influence the frequency, density and diversity of woody species.

Methodology

Study area

The study was conducted in the Mole National Park (latitude 9°12' - 10°06' N; longitude 1°25' - 2°17 'W with an elevation of 150 m). The Park is 4,577 km^2 located in the West Gonja District of Northern Region of Ghana (Figure 1). It contains a wide variety of plant species such as *Afrormosia laxiflora*, *Combretum adenogonium*, *Isoberlinia doka*, *Lannea acida* and ungulates including *Loxodonta africana* (Elephant) *Kobus kob* (Kob), *Kobus ellipsiprymnus* (Waterbuck) *Hippotragus equinus* (Roan), *Cephalophus natalensis* (Duiker), *Alcelaphus buselaphus* (Hartebeest), *Phacochoerus africanus* (Warthog) and a variety of bird species. The Park has a total of 32 fringe communities that also burn to attract game from the Park (Abukari and Mwalyosi 2018).

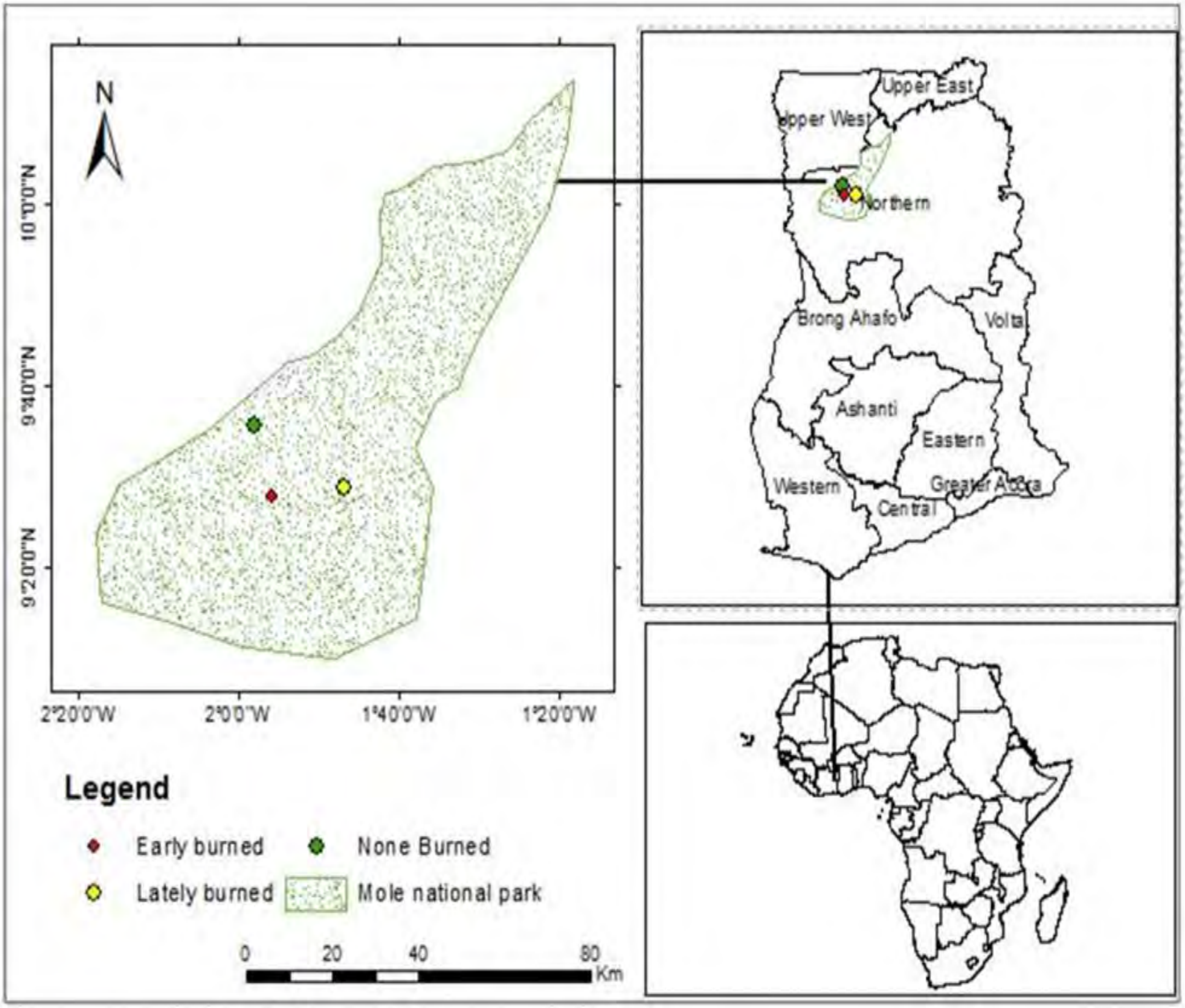

Figure 1. Study sites at the Mole National Park, Northern Region, Ghana. (Created by Hadgu Hishe, 2015)

The climate is semi-arid and sub-humid with a unimodal rainfall distribution. The rainy season begins in May and ends in October with a mean annual rainfall ranging from 900 mm to 1,000 mm during the peak between July and September (Oboubie and Barry 2005). The vegetation is Guinea savanna characterised by drought-resistant woody species mostly belonging to the Fabaceae and Combretaceae. The Guinea savanna occupies about 60% of the total land area of the Northern savanna zone (Oboubie and Barry 2005). The soils are laterite concrete formations of granite, voltaian shale and sandstones (Bennoah et al. 1991). They are low in organic matter, with low moisture content as a result of their high drainage characteristics (Mikkelsen and Langohr 1998; Owusu-Bennoah et al. 1991). The region experiences a long dry season which lasts November to April with little or no rainfall. Maximum temperatures, typically 40°C, occur towards the end of the dry season and minimum temperatures in December and January, with a mean annual temperature of 27°C. The Harmattan winds, which occur during December to early February, have a considerable effect on the temperatures in the region, which may vary between 14°C at night and 40°C during the day (Siaw 2001). These dry conditions and the strong Harmattan winds facilitate vegetation burning.

Data collection

Study design and sampling

Information on vegetation burning, obtained from the Faculty of Renewable Natural Resources, University for Development Studies and the Management of the Mole National Park, indicated that small portions in the Mole National Park are demarcated for early burning, late burning or no-burning for research purposes. The treatment blocks were demarcated in 1994 in areas that were already subjected to prescribed early and late burning and an area demarcated behind the Park information centre for no-burning i.e., one block per treatment. This is made possible because the treatments are bounded by roads, which serve as fire breaks, otherwise most part of the park is burnt annually. Burning is prescribed in the park for both late and early dry seasons, to prevent the vegetation from transitioning into thickets or closed woodland which may not be favourable for the variety of animals that in the park. Also, fire is used to stimulate grass growth for the animals to prevent them straying into the fringe communities (Sackey and Hale 2008).

Sampling

Sampling was carried out in blocks exposed to annual early burning (EB), late burning (LB) - and no-burning (NB). The early season burns are carried out in between November and December, depending on the time the rains end and the late dry season burning is carried out towards the end of February, up to the end of March.

Sampling of woody species was conducted to examine the impact of EB, LB and NB regimes on tree composition, diversity and densities. Twelve quadrats (10 m by 10 m) were systematically laid 50 m apart within each of the 200 m by 200 m treatment block. Thus, a total of 36 quadrats were sampled in all three treatments (Figure 2). This research was pseudoreplicated because all sample quadrat were located in a single block for each fire treatment (Figure 2).

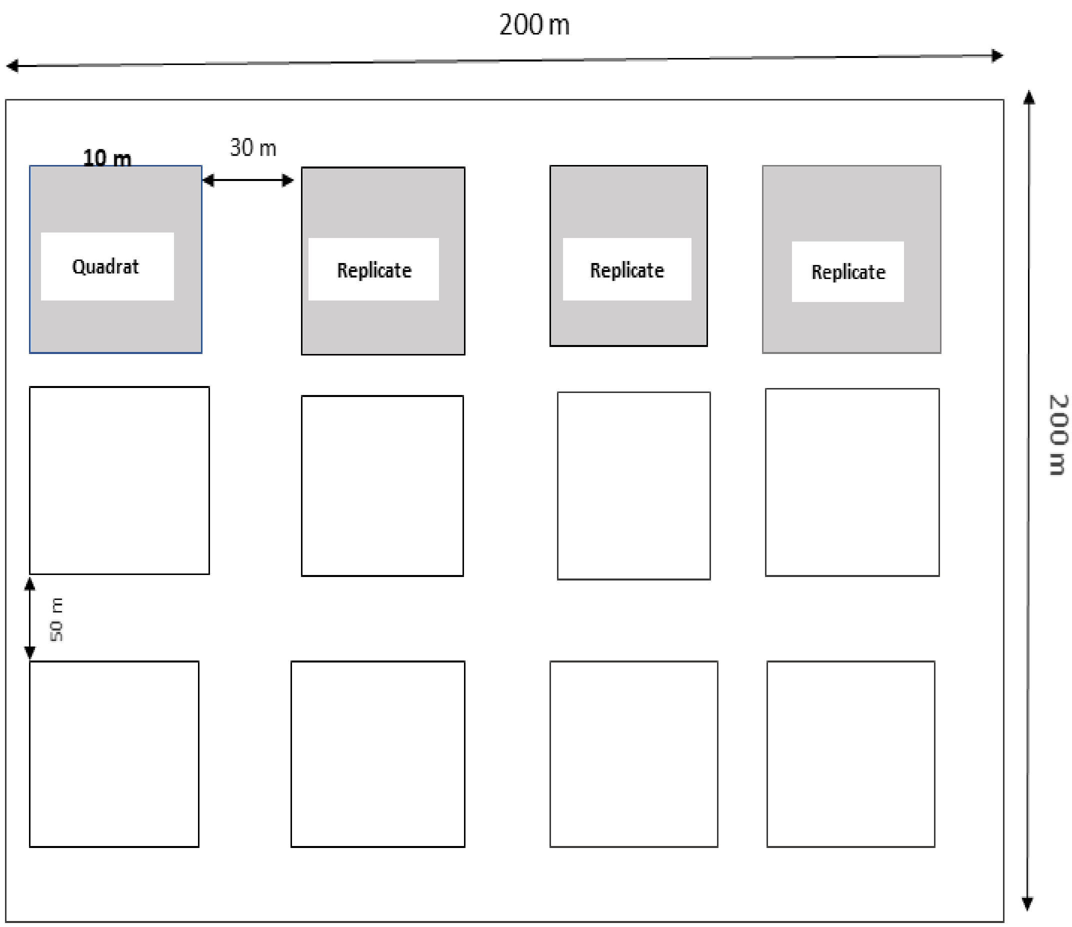

Figure 2. Sampling design per EL, LB and NB treatments

Vegetation survey

In each quadrat, the number of woody individuals with diameter at breast height ≥ 10 cm was recorded and each identified by their scientific names. The identification of species was done with the assistance of a Warden, who has been working in the park for over 30 years. A Geographical Positioning System was used to obtain the coordinates of the location of treatment plots; EB

(9°16'15.30"N, 1°51'02.90"W), LB (9°17'02.36"N, 1°49'08.11"W) and, NB (9°'15 40.20"N, 1°51'10.18"W). Sampling was done between 27th and 28th March 2015 and 29 and 1 April 2017, a few weeks after the late-season burning.

Data analysis

A Kruskal-Wallis test was used to compare mean ranks of the number of stems between treatments. Kruskal-Wallis does not assume that data is normally distributed. For each fire treatment, the species richness (number of species recorded) and their relative frequencies were assessed. Tree density, Pileou evenness, Simpson diversity, and Shannon-Wiener were calculated (Moore 2013). Diversity was measured with the number of stems and the index of Shannon & Weaver (1949) and Pileou evenness and Shannon-Wiener diversity and evenness was calculated for the three treatments:

$$H' = -p \sum i \ln pi$$

where pi is the proportion of individuals found in species i. pi = ni/N, where ni is the number of individuals in species i and N is the total number of individuals each treatment. An index value of 1 means that all groups have the same frequency.

Evenness was also calculated for the three treatments:

J = H'/ln(S) where H' is Shannon-Wiener diversity and S is the total number of species in a sample, across all samples in the three treatments. Species evenness ranges from zero to one, with zero signifying no evenness and one, a complete evenness.

The Simpson index (D) measures the dominance of a multispecies community was also estimated:

$$D = -\log \sum_{i=1}^{S} p_i^2$$

Where S is the species richness of a community and pi is the relative proportion of species i. The index can be modified to 1–D to give it the property of increasing as diversity increases -the dominance of a few species decreases (Moore 2013).

Samples from the three treatments were ordinated using Detrended Correspondence Analysis (DCA) to compare similarity and elucidate patterns of association in the study sites (Ayoub-Hannaa et al. 2013). Analysis was weighted by species presence in the three treatments. The axes were the proxy for variation in the vegetation which could relate with the time of burn and absence of fire. The DCA summarised major directions of variation for the species as found in the three treatments. Detrended Correspondence Analysis (DCA) and the other statistical analysis were done using the free software PAST v. 4.03 programme.

Results

Woody species frequency, density and diversity in early, late burnt and no-burn treatments

The relative frequency, density and the Shannon-Weiner diversity in the three treatments are presented in Table 1. A Kruskal-Wallis test showed that there was a statistically significant ($H= 37.74$, $p < 0.03$) difference between mean stem densities across the treatments. There were wide variations in mean density within and between treatments ranging between 0.0 - 212.5 stems/ha for EB, 0.0 - 370.8/ha for LB and 0.0 – 700/ha in NB treatments.

Twenty-seven different woody species, belonging to 14 families were identified across the three treatments. A total of 19 species were identified in the early burning treatment. Two species, *Terminalia avicennioides* Guill. & Perr (30%) and *Combretum adenogonium* Steud. Ex A.Rich. (19%) were found in relatively high frequency in this treatment. Fifteen species were identified in the late burn treatments. *Terminalia avicennioides* (54%) had the highest relative frequency. No-burn treatment had a total of 17 different species, of which *Vitellaria paradoxa* C.F. Gaertn (58%) was the most dominant. *Lannea acida* A. Rich, *Burkea africana* Hook and *Combretum molle* R. Br. ex G. Don were amongst the least occurring species in the no-burn treatment. Six species including *Afrormosia laxiflora* (Benth. ex Baker) and *Combretum molle* were common to all the treatments but had varying frequencies (Figure 3).

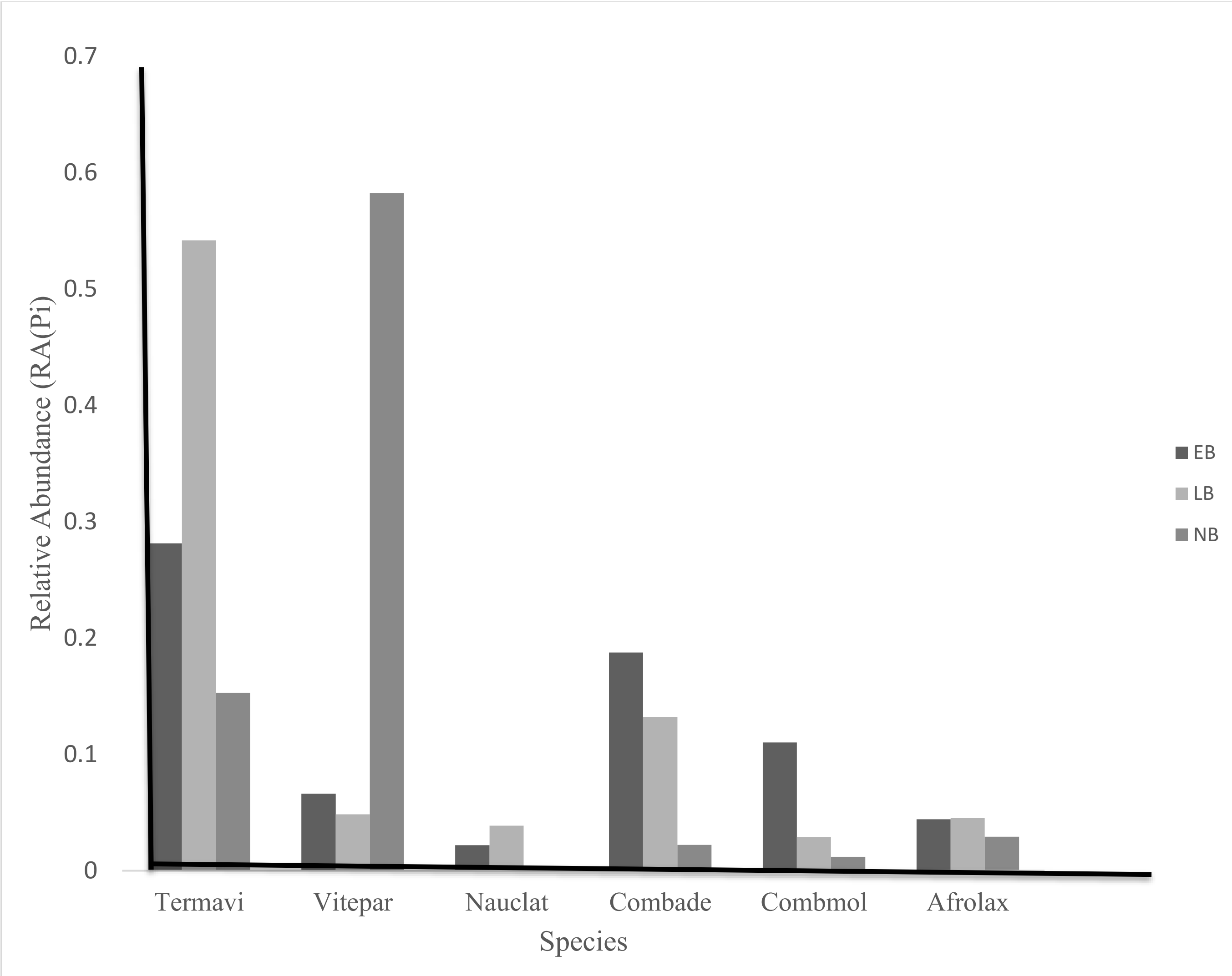

Figure 3. Most common and abundant species identified the three burn treatments (The species are listed by the first four letters of the genus and the first three of specific epithet recorded - Termavi= *Terminalia avicennioides*, Vitepar = *Vitellaria paradoxa*, *Nauclat*=*Nauclea latifolia*, *Combade=Combretum adenogonium, Combmol= Combretum mole, Afolax =Afrormosia laxiflora*)

Species with high relative frequencies belonged to Combretaceae, Fabaceae, Sapotaceae, Celastraceae, Meliaceae and Rubiaceae, while those occurring in low frequencies belonged to Anacardiaceae, Olacaceae, Ebenaceae, Moraceae, Bixaceae, Phyllanthaceae, and Asparagaceae. Combretaceae had the highest taxa frequencies of individual species - *Terminalia avicennioides* for instance, was 30% in the EB treatment, 54% in LB treatment and 15% in no-burn treatment.

Combretum nigrican Lepr. ex Guill. & Perr also a Combretaceae, on the other hand, had the lowest frequency in early burning and no records in late and no-burn treatments.

Seven species, including *Diospyros mespiliformis* Hochst. ex A. DC were common in the early burn and no-burn treatments (Table 1). *Anogeissus leiocarpa* (DC.) Guill. & Perr. was found in relatively high frequency (13%) in the no-burn treatment but low frequency in late burning treatment (0.6%) and *Trichilia rubescens* Oliv (1%) and (2.3%), *Pterocarpus erinaceus* Poir. (1%) and (1.3%), *Combretum nigrican* (0.5%) and (0.3%), were found common but in low frequencies in early burn and late burn treatments respectively.

Some species were exclusive to the different burning treatments but, had relatively low frequencies such as 0.2% for Dracaena palm in the no-burn treatment and 1.6% for *Detarium microcarpum*. *Isoberlinia doka* Craib & Stapf. and *Pteleopsis suberosa* Engl. & Diels were also present in early burning treatment only. *Cochlospermum angolense* Welw. ex Oliv., *Daniellia oliveri*, *Ficus glumosas* Delile, and *Anacardium occidentale* were found in the late burning treatment only. *Dracaena* palm and *Pseudocedrela kotschyi* (Schweinf.) were identified in the no-burn treatment only. *Vitellaria paradoxa* was present in all treatments, with the highest frequency in no-burn treatment. All other species present in the no-burn treatment were also present in either early burning or late burning treatment (Table 1).

Woody plant density varied across all treatments with the no-burn treatment having the highest (598 stems/ha) and early burn treatment the lowest (187 stems/ha). The Shannon Wiener diversity index was the same (0.5±0.5) for late burning and no-burning treatments, but varied with early burnt treatment which had the highest diversity (0.7±0.4). All treatments exhibited a complete evenness (0.9-1.0). However, species with relatively low numbers were more even in occurrence than the dominant species in all the treatments (Table 1).

Table 1. Woody species density (mean ± standard deviation), relative frequency and diversity in three treatments

Species	Early burning (N =12)		Late burning (N=12)		No-burn (N=12)		Species code
	Mean density/ha	Frequency (%)	Mean density/ha	Frequency (%)	Mean density/ha	Frequency (%)	
Afrormosia laxiflora	33.3±3.7	4.4	58.3±5.7	4.5	70.8±4.2	3.0	*Afrolax*
Anacardium occidentale	0.0±0.0	0.0	25.0±1.9	2.0	0.0±0.0	0.00	*Anacocc*
Anogeissus leiocarpa	0.0±0.0	0.0	8.33±0.6	0.6	325±23.8	13.0	*Anoglei*
Burkea africana	20.8±1.8	2.7	0.0±0.0	0.0	4.2±0.5	0.2	*Burkafr*
Cochlospermum angolense	0.0±0.0	0.0	33.3±2.8	2.6	0.0±0.0	0.0	*Cochang*
Combretum adenogonium	141.7±10.7	18.6	170.8±4.6	13.2	54.2±2.22	2.2	*Combade*
Combretum molle	83.3±7.2	11.0	37.5±3.9	3.0	29.2±2.9	1.2	*Combmol*
Combretum nigrican	4.2±0.5	0.5	0.0±0.0	0.0	8.3±1.0	0.3	*Combnig*
Crossopteryx febrifuga	12.5±1.4	1.6	0.0±0.0	0.0	8.3±1.0	0.3	*Crossfeb*
Daniellia oliveri	0.0±0.0	0.0	20.8±1.5	1.6	0.0±0.0	0.0	*Danioli*
Diospyros mespiliformis	4.2±0.5	0.5	0±0.0	0.0	12.5±0.95	0.5	*Diosmes*
Detarium Microcarpum	12.5±1.1	1.6	0±0.0	0.0	0.0±0.0	0.0	*DetaMic*
Dracaena palm	0.0±0.0	0.0	0±0.0	0.0	4.2±0.5	0.2	*Dracpal*
Ficus glumosa	0.0±0.0	0.0	25±1.9	1.9	0.0±0.0	0.0	*Ficuglu*
Hymenocardia acida	12.5±1.1	1.6	41.7±3.8	3.2	4.2±0.5	0.3	*Hymeaci*
Isoberlina doka	50.0±3.9	6.0	0±0.0	0.0	0.0±0.0	0.0	*Isobdok*
Lannea acida	4.2±0.5	0.5	0±0.0	0.0	8.3±1.0	0.3	*Lannaci*
Maytenus senegalensis	33.3±2.9	4.4	0±0.0	0.0	12.5±1.5	0.5	*Maytsen*
Nauclea latifolia	16.7±1.3	2.2	50±4.8	3.9	4.2±0.5	0.3	*Nauclat*
Piliostigma thonningii	4.2±0.5	0.5	8.30.5	0.6	20.8±1.5	1	*Pilitho*
Pseudocedrela kotschyi	0.0±0.0	0.0	4.2±0.5	0.3	70.8±5.3	3.0	*Pseukot*
Pteleopsis suberosa	33.3±3.7	4.0	0.0±0.0	0.0	0.0±0.0	0.0	*Ptelsub*
Pterocarpus erinaceus	8.3±0.9	1.0	16.7	1.3	0.0±0.0	0.0	*Ptererin*
Terminalia avicennioides	212.5±15.4	30.0	700.0±37.0	54.2	370.8±10.8	15.0	*Termavic*
Trichilia rubescens	8.3±0.7	1.0	29.2±1.3	2.3	0.0±0.0	0.0	*Tricrub*
Vitellaria paradoxa	50.0±3.9	6.0	62.5±2.21	4.8	1,412.5±24.5	58.0	*Vitepar*
Ximenia americana	8.3±0.7	1.0	0.0±0.0	0.0	8.3±0.57	0.3	*Ximeame*
Total number of stems	187		369		598		
Shannon-Weiner diversity	0.7±0.4		0.5±0.5		0.5±0.5		
Simpson_1-D	0.3±0.4		0.4±0.2		0.3±0.28		
Evenness_e^H/S	0.9±0.1		0.9±0.1		1.0±0.1		

Relationship between time of burning and species composition

The DCA showed a moderately strong positive association between burning time and species. The analysis showed a cumulative percentage of 68% of variation on all four axes. The first and second axes contributed 53% and 12% variation, respectively. Most of the species found along axis1 had a fairly strong positive association to early or the late burn treatments than no-burn treatment with a few species (e.g., *Lannea acida* and *Piliostigma thonningii*) spreading away from the majority of species on the second axis and *Daniellia oliveri* (268 DCA scores), *Ficus glumosa* (271 DCA scores) and *Cochlospermum angolense* grouping on fourth axis of the ordination (Table 2 and Figure 2). Species such as *Dracaena* palm and Vitellaria paradoxa are positively correlated to the no-burn treatment. Species including *Diospyros mespiliformis* (-10 DCA scores) had a strong negative association with *Daniellia oliveri*, *Ficus glumosa* and *Cochlospermum angolense* grouping which had a strong negative correlation with the no burn treatment. The ordination shows an association of *Terminalia avicennoides* (142 DCA scores) and *Ximenia americana* (85 DCA scores) with LB and EB (Table 2). There was a negative correlation between *Anogeissus leiocarpa* (-36 DCA scores) and the rest of the species as observed in Figure 3. The DCA scores are presented in Table 2.

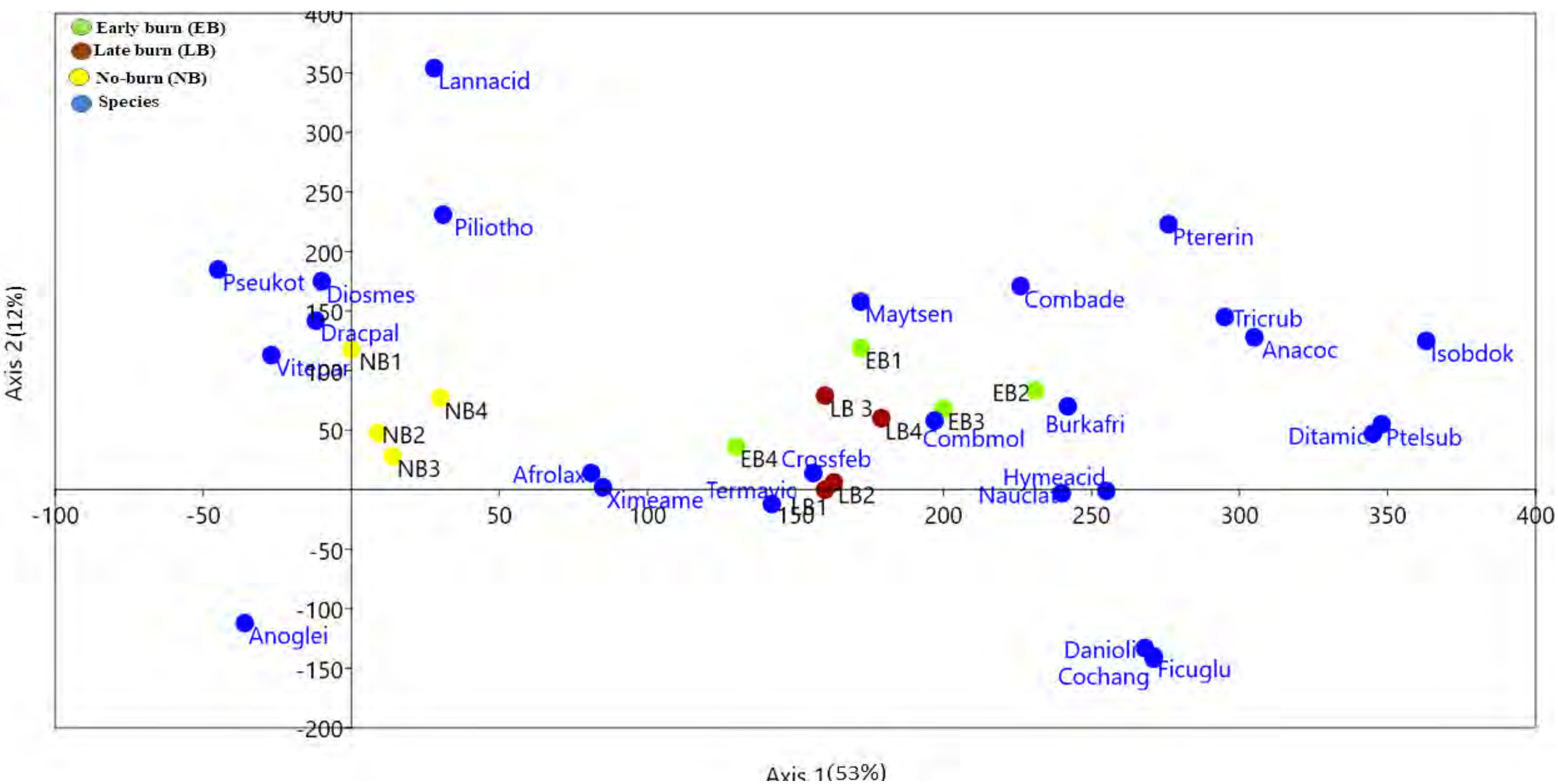

Figure 3. DCA Scatter plot of species in the three burn treatments (The species are listed by the first four letters of the genus and the first three of specific epithet recorded - Table 1)

Table 2. Scores from DCA analysis

Species	**DCA scores**		
	Axis 1	Axis 2	Axis 3
Afrormosia laxiflora	81	14	-69
Anacardium occidentale	305	128	-412
Anogeissus leiocarpa	-36	-112	146
Burkea Africana	242	70	58
Cochlospermum angolense	271	-142	-134
Combretum adenogonium	226	171	152
Combretum mole	197	58	96
Crossopteryx febrifuga	156	14	107
Daniellia oliveri	268	-133	144
Detarium microcarpum	345	47	64
Diospyros mespiliformis	-10	175	-20
Dracaena palm	-12	142	30
Ficus glumosa	271	-140	-44
Hymenocardia acida	255	-1	-173
Isoberlina doka	363	125	162
Lannea acida	28	354	257
Maytenus senegalensis	172	158	283
Nauclea latifolia	240	-3	-38
Piliostigma thonningii	31	231	133
Pseudocedrela kotschyi	-45	185	-68
Pteleopsis suberosa	348	55	135
Pterocarpus erinaceus	276	223	322
Terminalia avicennioides	142	-12	17
Trichilia rubescens	295	145	36
Vitellaria paradoxa	-27	113	51
Ximenia americana	85	2	87
Treatments			
EB 1	172	119	122
EB 2	231	83	85
EB 3	200	68	94
EB 4	130	36	23
LB 1	160	0	0
LB 2	163	6	51
LB 3	160	79	44
LB4	179	60	35
NB1	0	118	47
NB 2	9	48	66
NB 3	14	28	71
NB 4	30	77	38

Discussion

Relative frequency, density and diversity of species in early, late and no-burn treatments

The characteristics of trees in the Guinea savanna ecological zone are defined by the response to regeneration after fire, thus most are fire and drought resistant (Russell-Smith et al. 2012; Sinare and Gordon 2015). The most common species identified belonged to the Combretaceae and Fabaceae which regenerate from seed, but also through resprouting. These species may not need a long time for regeneration after fire (Lovett and Haq 2000; Sackey and Hale 2008).

Most Combretaceae species and Fabaceae are tolerant to fires, drought as well as fire exclusion, with a high probability of regeneration from resprouting after fire and other disturbances (Higgins et al. 2000; Sackey and Hale 2008). This explains their high presence in all the treatments. The seeds of these species are normally dehiscent or indehiscent and need fire to enhance germination which reflected in their low frequency in the no-burn treatment. Their high presence in late burn plots presupposes that these species are also tolerant of late-season fires. However, in this study, trees of ≥10 cm dbh were considered because in EB and LB plots most saplings and seedlings were almost non-existent especially in late season burnt plot which could be attributed to the biomass burning coupled with the dry season and grazing animals in the Park. *Vitellaria paradoxa* (Sapotaceae), on the other hand, does regenerate easily by seed and also by resprouting as revealed by Lovett and Haq (2000), hence the highest number of individual recorded in the no-burn treatment.

Except for *Anacardium occidentale*, which is an exotic species, all other species are native to the Guinea savanna (Sinare and Gordon 2015; Cardoso et al. 2016). *Anacardium occidentale* was most probably brought in by animals or some other agents of dispersal from fringe villages that grow it on their farms. Also, *Anacardium occidentale* was found in late burn treatment probably because the seed coat containing double-walled shell with hard epicarp, mesocarp is able to germinate with late season fires.

The abundant and widespread species of the Combretaceae and Fabaceae confirm other studies that Sudano-Guinean savanna woodland species typically fall within these families (Aubréville 1958). They thrive under harsh weather conditions and areas where fires are common. Although, *Parkia biglobosa* is known to be a dominant species in the Guinea savanna woodland (Aubréville 1958) the species was not recorded in any of the treatments in this study and confirms the IUCN listing of the tree as vulnerable. Indeed, Combretaceae species that previously defined the Guinea savanna woodland recorded very low occurrences, thus may be threatened by too frequent fires, *Combretum adenogonium* is able to thrive under late burning treatment (Legris and Blanco 1979). The reduced number of stems may affect some animals that depend on these species for food and shelter and the gradually changing the vegetation structure and composition of the Sudano-Guinean savanna of Ghana. Most of the species identified in the early and the late burning treatments were present in the no-burn treatments indicating that no burn may be good for all species but affect the abundance of some species if fire exclusion is practised. *Dracaena* palm which was solely found in the no-burn treatment is known to thrive well in the rainy season but can also withstand drought (Marrero et al. 1998). It was found in low frequency because it is a rare species according the IUCN Red list (Aubréville 1958; Marrero et al. 1998).

Species found exclusively in the burnt treatments are hardy and can withstand the frequency of fire. Practising no-burn may suppress the growth of some savanna species such as those belonging to the Combretaceae. *Combretum adenogonium* for instance seemingly requires fire to germinate. Also, the high leaf litter observed during sampling in the no-burn treatment may not be a desirable condition for the growth of light and fire tolerant species such as *Combretum* and *Nauclea spp*, thus the lowering prevalence of such species (Cardoso et al. 2016). The conditions of shade and no-burning on the other hand, has been found to promote species such as *Piliostigma thonningii* (Gignoux et al. 2009, 2016). This is confirmed in this study as highest density (20.8±1.5) of *Piliostigma thonningii* was found in the no-burn treatment than burnt treatments.

The relatively low tree density identified in the two burn treatments (compared to the no-burn treatment) indicates that burning in general, has a negative influence on tree density as it was also revealed in a study conducted in the savannas of Ghana, Cote d'Ivoire (Brookman-Amissah et al. 1980; Bassett et al. 2003) and South Africa (Shackleton and Scholes 2000). Nevertheless, the higher diversity observed in early burn compared to late burn treatment suggests that early burning favours the growth of different species in the savanna. There is a possibility that fire did not destroy seeds and saplings of some species, but rather enhanced their germination, thus, increasing the diversity in early burn treatment (Gijsbers et al. 1997).

Late burning on the other hand, had an adverse effect on diversity, probably because late season fires are usually hot and some species may not be able to survive the intensity. Thus, the observation in this study is that late season burning is not favourable for species diversity (Cardoso et al. 2016). However, some studies have shown that decreasing diversity can be detrimental for some animals and plants species (e.g., Fontain et al. 2009; Ouédraogo and Thiombiano 2012; Mensah et al. 2014). The authors explained that different animals prefer different habitat types and some plant species co-occur better in some habitat than others.

In contrast to low diversity in the late burning treatment, late burning promoted the densities of *Terminalia avicennioides* and *Combretum adenogonium* in this study. However, most prescribed burning plans recommend early burning over late burning (Amanor 2002; Makela and Hermunen 2007). So that as described by Cardoso et al. (2016), regeneration of species under both burn treatment could be a win for some species while other species lose. Thus, the comparatively high mean density of *Combretum* species observed in the late burning treatment in relation to early burning is because their seeds germinate easily with hot fires and there is not much damage to trees because they shed their leaves before the late season fires are ignited (Higgins et al. 2000; N'Dri et al. 2018; Gomes et al. 2020). Williams et al. (1998), however, found that late season fires were devasting.

The high tree density in the no-burn treatment confirms that savannas are not climax vegetation; when the disturbance is minimised, they can gradually transform into a woodland or forest (Bond and Midgley 2001; Bassett et al. 2003). Indeed, no-burning can enhance seeds of shade-loving species buried in the soil to germinate and grow. However, the high mean densities observed within the no-burn treatment could also give rise to more competition which may not be favourable for other species but for *V. paradoxa*. Thus, promoting the occurrence, abundance and coexistence of limited number of species.

Although, fire plays a role in the structure and function of savannas, a report by the Park management indicated that some species are associated with some types of soil in the Park, which implies that the species identified in the various treatments may not solely be influenced by fire but also by the soil type (Shackleton and Scholes 2000; van Wilgen 2009; Dzwonko et al. 2015). Nonetheless, all the dynamics in species density, diversity and richness within and between treatments may as well depend on the intensity, frequency, duration of fire, topography and other environmental factors (Trollope and Trollope 2002; Gambiza et al. 2005; Cardoso et al. 2016).

Conclusion

This study revealed that seasonal burning had a negative effect on tree density, relative to no-burn treatments. No-burning, however, increased tree density, rather than diversity. Burning promoted the occurrence of *Terminalia avicennioides* and some *Combretum* species, whereas no-burning was a favourable condition for *Vitellaria paradoxa* (Sapotaceae). Thus, no-burning practices would increase the populations of species that are not fire-dependent. The protection of *Vitellaria paradoxa* from fire and other disturbances would increase populations which would have greater benefits for communities in the north of Ghana because of the role it plays in rural livelihoods.

As observed by many authors, fire plays a very important role in sustaining savanna ecosystems. However, no-burning practices can be encouraged to restore species and fire degraded habitats (as a result of too frequent and repeated fire cycles without monitoring). The observation is that both monitored or prescribed burning, and no burning have good implications for the tree species density, diversity and richness.

Thus, the study revealed that the different times of burning influenced vegetation differently. Hence, the Park's policy of burning different sites at different times of the year is protective of indigenous species and maintaining the woodland savanna. However, there is a need to monitor the effects of the annual fires in the study site to ascertain what the Park is gaining or losing in terms of animal species' diversity and density.

This study could be scaled-up for studies on burning, species diversity and density and also for further studies on unmanaged areas with unplanned fire regimes. I, therefore, recommended community sensitization and collaborative stakeholder engagement on the impact of burning practices on species including economic species like *Vitellaria paradoxa*, whose fruits and nuts are highly valued non-forest timber product in the Guinea savanna.

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CHAPTER 4: THE EFFECTS OF FIRE ON THE POPULATION STRUCTURE AND ABUNDANCE OF *ANOGEISSUS LEIOCARPA* AND *VITELLARIA PARADOXA* IN A WEST AFRICAN SAVANNA PARKLAND

Abstract

West African savannas experience a prolonged dry season with Harmattan winds which facilitate large and persistent biomass burning from November to April. The fires are mostly caused by humans, mainly in pursuit of day-to-day livelihood activities. We examined how fire frequency and land use influences the population structure and abundance of two economically important woody species *Vitellaria paradoxa* (Shea tree) and *Anogeissus leiocarpa* (African Birch) in three categorised fire frequency districts and six land use types in the Guinea savanna, Ghana. We calculated the stand basal area, mean densities of juveniles and adult trees and Simpson’s index of dominance. Eight diameter size classes of each species were analysed by comparing their observed distributions to a three-parameter Weibull distribution across the land use types. High mean densities of *A. leiocarpa* and *V. paradoxa* were found in low (207±9.5 stems/ha) and high (241±4.7) frequency fire districts as well as sacred groves (22.7±29.7 stems/ha) and fallows (15.3±2.2 stems/ha), respectively. Mean density of juveniles of both *A. leiocarpa* (248.0±89.1 stems/ha) and *V. paradoxa* (68.0±29.7stems/ha) were higher in unburnt woodlands than in the other land use types. *A. leiocarpa* was absent in fallows and burnt crop fields. An inverse J-shaped distribution was found in low fire frequency districts for *Anogeissus leiocarpa* and somewhat J-shaped distribution for *V. paradoxa* in high fire frequency districts. The distribution in the moderate fire frequency districts shows unstable populations for both species. The absence of *A. leiocarpa* in burnt crop fields and the decrease of some size classes of *V. paradoxa* in both burnt and unburnt crop fields indicate the need for sustainable conservation of both species. The near inverse J-shape distribution found in sacred groves for both *A. leiocarpa* and *V. paradoxa* implies that these species thrive with minimal anthropogenic disturbance. However, *A. leiocarpa* showed good recruitment and high population in low fire frequency areas and sacred groves, thus, can be protected through cultural conservation practices such as early burning and no burning. *Vitellaria paradoxa*, on the other hand, survives in all frequency fire areas, burnt and unburnt land use types, thus, is likely easy to conserve in fire prone areas such as West African savannas.

Keywords: fire, Guinea savanna, land use, size class distribution, woody species

Introduction

The structure, composition and function of savannas are dependent on the interplay of climatic and edaphic factors (N'Datchoh et al. 2015; Veenendaal et al. 2018). However, humans have further influenced savannas through traditional land use systems which resonate with social and cultural belief systems in different places around the world (Jurisch et al. 2012; Trauernicht et al. 2013, 2015; Fache and Moizo 2015; Sluyter and Duvall 2016). Several studies have revealed the extensive anthropogenic use of fire, in pursuit of rural socio-cultural and livelihood activities across African savannas (e.g., Bassett et al. 2003; Archibald 2016; Knowles et al. 2016; N'Datchoh et al. 2015; Veenendaal et al. 2018). These activities include land preparation for crop production (e.g., slash and burn), natural pasture management, hunting, weed/grass control and honey harvesting (Lopez-Merino et al. 2009; Dayamba et al. 2010; Dwomoh and Wimberly 2017, Nyogesa and Vacik 2018).

The dynamics and survival of woody species in most African savannas is thus, driven by subsistence land use and fire practices (Schumann et al. 2011; Jurisch et al. 2012) which has influenced the vegetation structure and diversity. West African savannas for instance, are characterised by fire and drought resistant and tolerant species as a result of the high frequency of various fire-assisted socio-cultural and livelihood practices (Rose Innes 1972). Trees may as well, be sparsely distributed or scattered depending on the extent of human interference through these land use practices and the frequency of fire use (Bassett et al. 2003; Bagamsah 2005).

A few studies have shown that woody species in savannas respond differently to fire regimes – with intolerant species being killed (Cochrane and Barber 2009; Schumann et al. 2011; Jurisch et al. 2012). Some studies have, however, indicated that fire effects are dependent on the fire frequency, stem size, height of the plant and the species (Cochrane and Barber 2009; Schumann et al. 2011; Jurisch et al. 2012; Coughlan 2014). Additionally, fires have also been reported to induce growth of some species by breaking dormancy of hard-coated seeds thereby influencing species regeneration (De Brito Freire-Jr and Motta 2011; Deus and Oliveira 2016). Lykke (1998) reported that species that are best adapted to prevailing disturbance regimes can become the most abundant. However, the effects of traditional fire use practices on the population structure of economically important woody species in the Sudano-Guinean savanna woodlands and (e.g., forest reserves, thickets, groves) and parklands (e.g., croplands, bush fallows natural pastures) remains understudied (Lykke 1998; Laris 2002). Studies on the structure of vegetation in different savannas around the world have invariably focused on

[2]particular plant species in protected areas (e.g., Hu et al. 2014; Cousins et al. 2014; Inoussa et al. 2017; Mengich et al. 2020) with much fewer studies in unprotected areas including cultural landscapes such as the agroforestry parklands of West Africa. A few studies have been conducted in protected sites, unprotected areas, different climatic gradients and land management regimes, but the use and the effects of fire are mentioned only in passing (Schumann et al. 2010; Glèlè Kakaï et al. 2011; Attua and Pabi 2013; Aleza et al. 2015; Mensah et al. 2016). Also, most studies (e.g., Bagamsah 2005; Appiah 2013; Dwomoh and Wimberly 2017) on woody species in the Guinean savanna have been conducted in woodlands and forest reserves excluding croplands which are inherently embedded in parklands where fire is mostly applied (Ramoa et al. 2020). For instance, Ramoa et al. (2020) detected more small fires from croplands (less than a hectare - not easily detected by MODIS) than large fires from the woodlands in sub-Saharan Africa. Thus, there is evidence of frequent fires in both woodlands and croplands (Dwomoh and Wimberly 2017; Ramoa et al. 2020). The frequency of fire use combined with other land use practices may result in a decline in the populations of some woody species, including economically important ones such as *Vitellaria paradoxa* C. F. Gaertner (Shea tree) and *Anogeissus leiocarpa* (DC.) Guill. & Perr. (African Birch) (Schumann et al. 2010; Aleza et al. 2015).

The two species are prevalent in farmed, woodland and cultural landscapes of the Sudanian-Guinean savannas of West Africa (Boffa et al. 2000; Lovett and Haq 2000). Both species have long been associated with human movement and settlement (Boffa et al. 2000; Lovett and Haq 2000). Wong and Hall (2004) indicated that *V. paradoxa*, for instance, accounted for 70–90% of the mature trees in farmed land and under 20% in natural woodland. So that the shea germplasm for instance, reflects a conscious selection over millennia. Thus, it may be described as semi-domesticated (Boffa et al. 2000; Lovett and Haq 2000). The over-exploitation of *V. paradoxa* and *A. lieocarpa* for timber, firewood and charcoal production has been reported in

[2] Amoako, E. E. and Gambiza, J. (2021). Effects of fire on the population structure and abundance *of Anogeissus leiocarpa* and *Vitellaria paradoxa* in a West African savanna parkland. Acta Oecologica 112, 103745. doi.org/10.1016/j.actao.2021.103745

Benin, Burkina Faso and some other countries in West Africa (Assogbadjo et al. 2010; Schumann et al. 2011; Aleza et al. 2015; Sanogo et al. 2015). At the global level, *V. paradox*a and *A. lieocarpa* have been classified by the International Union for Conservation of Nature (IUCN) Red List as Vulnerable and Threatened, respectively (IUCN/IENR 1998). The prolonged and persistent fire use for livelihood purposes affects populations of both species differently in these savanna landscapes (Lykke 1998; Laris 2002, 2011). For instance, the Guinea savanna woodland and parklands of Ghana have experienced 30% - 40% of the total fire occurrence in the last thirty years and may have varying effects on the species in this ecological zone which has never been ascertained (Kugbe 2014).

Size class models have been used to compare the population structure of woody species under different land use practices and management systems (Glèlè Kakaï and Sinsin 2009; Cousins et al. 2014). A size class model is a whole stand approach of assessing both natural and human influences on woody vegetation (Condit et al. 1998; Lykke 1998; Glèlè Kakaï and Sinsin 2009; Cousin et al. 2014). Lykke (1998) postulates that vegetation population change in disturbed savanna systems is the most influential parameter on size class distribution (SCD) as against systems with fewer anthropogenic stressors. Nonetheless, the model provides details on stand structure based on stand-level attributes, such as stand basal area and mean densities of juveniles and mature trees. A greater abundance of juveniles relative to adults, results in an inverse J-shaped distribution indicating a growing population (Condit et al. 1998; Aleza et al. 2015; Inoussa et al. 2017). Thus, for highly human influenced systems such as the Guinea savanna parklands of West Africa, knowledge on the fire use and the population structure of species is important (Boffa et al. 2000; Wong and Hall 2004). Information on size class could inform strategies for sustainable management and conservation of economically important woody species, as well as enhance livelihoods of the people who directly depend on these species.

However, some studies in agroforestry parklands in Senegal, Burkina Faso and Mali have shown that disturbance can destroy nearly all small diameter stems, resulting in inconsistences in recruitment into medium and larger class (Lykke 1998; Laris 2002; Ouédraogo 2013). Lykke (1998) also, indicates that some juveniles will not survive into maturity, and this is worst in fire dominated environments. Bell-shaped distributions were found to be most common (more than 50 %) of the plant populations of long-lived and slow-growing species in South Africa (Venter and Witkowski 2013). A reverse J-shaped distribution curve as an indicator of stability and a growing population may not always hold for some species especially in a disturbed environment (Cousins et al. 2014).

In line with the social-ecological system conceptual framing of this thesis, it was important to find out the effects of the anthropogenic fires on the system (i.e., the Guinea savanna) and the units (vegetation and soil). Analysis of stand level responses to early, late and no burn was discussed in Chapter three. In this Chapter (four), the studysought to examine and ascertain how the frequency of fire use and different land uses affect the population parameters and structures of *Vitellaria paradoxa* and *Anogeissus leiocarpa*. I therefore hypothesised that the use of fire in different fire frequency districts and land uses can influence the abundance and population structure of *A. leiocarpa* and *V. paradoxa* differently.

Methodology

Study area

The Northern region is located in the Guinea savanna (70,383 km^2) of Ghana and lies between 8 - 10° N and 0 -3° W (Dwomoh and Wimberly 2017) and occupies almost a third of the land area of the country (Figure 1). The region lies between the sub-humid and semi-arid zones. The rainy season begins in May and ends in October with an average annual rainfall of 1,100 mm. The region has an annual mean temperature of 27°C. The dry season starts in November and ends in March/April (Kranjac-Berisavljevic et al. 1999; Shorocks and Bates 2015)

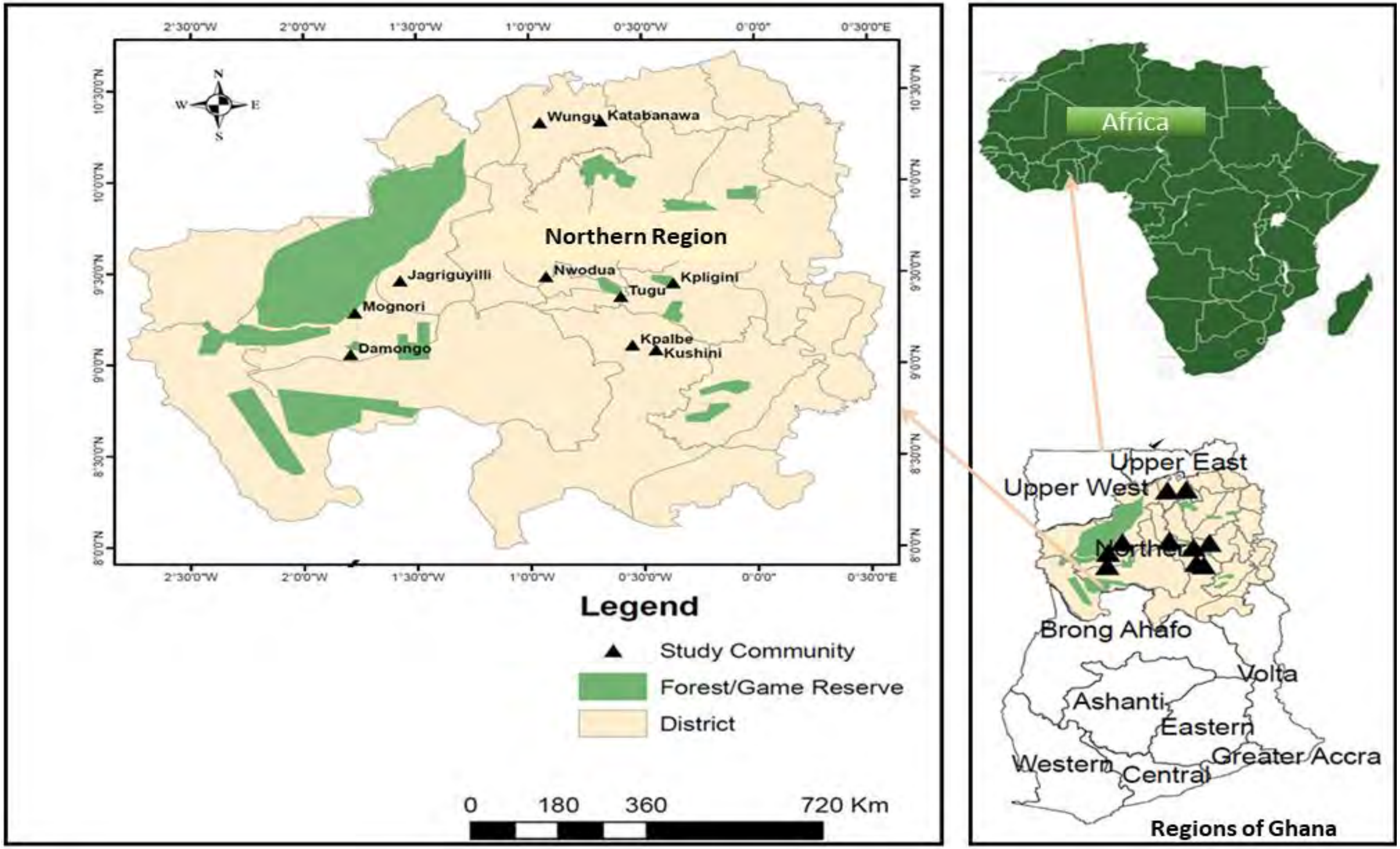

Figure 1: Study area showing study communities and reserves (Created by Bernard Batuuwie, 2018)

Minimum night temperatures (~14 °C) occur in December and January. Maximum day temperatures (38°C) occur in March towards the end of the dry season. The Harmattan winds, which occur from December to March, have a considerable effect on the temperatures in the dry season. The lowest relative humidity (12%) is recorded in December and January, and the highest (80%) in August, the peak of the rainy season (Kranjac-Berisavljevic et al. 1999).

The vegetation is Guinea savanna which is categorised into closed woodland, open woodland and wooded savanna and parklands depending on the cover and structure of the woody vegetation (Bagamsah 2005; Shoyama et al. 2018). Dominant tree species belong to the families Combretaceae and Fabaceae. These families trees are characterised as fire-tolerant, fire-resistant and drought-tolerant (Boffa 1995; Parr and Andersen 2009). The natural vegetation is gradually being depleted, as trees of most species are deliberately removed from the savannas, leaving a few species of economic importance (*V. paradoxa* and *P. biglobosa*) interspersed with food crops, referred to as parklands (Blench 2001; Blench and Dendo 2004). Crop fields are expanding into the wooded areas. Between 1984 and 2015, crop fields increased from 20% to 50% whereas closed woodland and grassland decreased by 20% from 28% and 24%, respectively (Shoyama et al. 2018). However, there are some sacred groves in communities where some original savanna species remain (Poreku 2014).

Generally, soils are characterised as savanna Ochrosols, ranging from black alluvial soils and salty brown soils to stony/gravelly soils which are classified in the 'World Reference Base' as Luvisols and Fluvisols (Mikkelsen and Langohr 2004). They are light sandy soils which have low water retention capacity, and their corresponding Ochrosols are moderately drained and less prone to degradation (Mikkelsen and Langohr 2004).

Common land use practices include crop farming, animal rearing, hunting and charcoal production. Crop farming is mainly rain-fed and the primary crops grown are maize, sorghum, rice, millet, yam, groundnuts and different varieties of beans. Crop farming is integrated with the rearing of livestock (sheep, goats and poultry) (Kranjac-Berisavljevic et al. 1999). Hunting (communal and individual), fuelwood harvesting, charcoal production and petty trading are primary alternative sources of livelihood in the dry season (Blench and Dendo 2004). The indiscriminate dry season fires are likely to be a contributory factor to the decreasing number of woody plants in the Guinea savanna (Blench and Dendo 2004).

Study species

Anogeissus leiocarpa (Combretaceae)

Anogeissus leiocarpa is one of the main tree species associated with the Sudano-Guinean savanna parklands ranging from the Sahara to the Equatorial Forest of Africa (White 1983). The species is found from the extreme Sahel to the Guinean forest savanna transitional zone (Hennenberg et al. 2005). Sexual regeneration of *A. leiocarpa* is nearly non-existent because of the absence of a soil seed bank; hence, asexual regeneration, ex-situ conservation and sustainable use of the species are essential for growth and survival of the species (Sanogo et al. 2015). The tree is shade tolerant, drought resistant, but very sensitive to fire in the Sudano-Guinean savanna (Sobey 1978; Hennenberg et al. 2005). The species is under intense anthropogenic pressure for its uses in traditional medicine, as a preferred species for charcoal, and as a dye and tannin for the local cloth industry (Sanogo et al.2015; Mattana et al. 2018).

Vitellaria paradoxa (Sapotaceae)

Vitellaria paradoxa (Shea Tree) is native to the Sahel region of West Africa and endemic to the Sudano-Guinean savanna and parklands (Boffa 1995). It is a preferred species in the traditional parkland agroforestry systems of West Africa (Boffa 1995), hence becoming a dominant species in most Guinea savanna parklands. The tree grows to an average height of 20 m and up to 1 m in diameter, with a densely-branched crown (Boffa 1995). It is deciduous but appears evergreen because new leaves emerge as the old ones fall. *Vitellaria paradoxa* has a thick, deeply fissured, and fire-resistant bark (Boffa et al. 2000). The butter derived from the kernels is used in cooking, cosmetics and pharmaceuticals, rendering it a high-value species for both local and international use (Naughton et al. 2015). *Vitellaria paradoxa* is difficult to propagate (Lovett and Haq 2000). Although efforts are made at employing local regulations to protect the tree, the species has been overexploited for lumber, timber and fuelwood. Tree populations and the habitat are suffering from uncontrolled annual fires, agricultural encroachment and increasing human population pressure (Shoyama et al. 2018) (Figure 2 - A and B) show the two species interspersed with crops in West Africa.

Figure 2 A: *Anogeissus leiocarpa* in a traditional agroforestry parkland of Benin with inserted pictures of *i* - leaves with fruits and ii- bark

Figure 2: B: *Vitellaria. paradoxa* (Tom-Dery 2015) in Guinea savanna agroforestry parklands of Ghana with inserted pictures of i - leaves with fruits and *ii*- bark

Study design and data collection

Fire frequency data were obtained from the University of Energy and Natural Resources, Sunyani, Ghana, in collaboration with the CSIR-Meraka Institute, South Africa. Eighteen districts in the Northern region of Ghana with data on fire counts were categorised into high fire frequency (6,213-15,254 counts/5 years), moderate fire frequency (2,804-6,213 counts/5 years) and low fire frequency (487-2,804 counts/5 years) districts. Ten communities in six districts with fire data were selected with the assistance of the Regional Forestry Commission officials in Tamale. Three communities were purposively selected (Lavrakas 2008) to include those that practice no-burning and those with large sacred groves, for comparison between burnt and unburnt areas.

The size of woodlands varied from one community to another, ranging up to several hundreds of hectares. Crop fields varied between one and two hectares and may be left fallow for a maximum of seven years (Songsore 1996). Sacred groves vary between 10 m^2 and 1,000 m^2 (Telly 2006). In each community, fallows, sacred groves, unburnt and burnt woodlands, unburnt and burnt crop fields were purposively selected. Fallows are farmlands that are left to “rest” from farming for up to seven years (Songsore 1996). Sacred groves are portions of community landscapes that have not burnt for several decades with no or minimum human interference (Ormsby 2012; Poreku 2014). The groves are protected physically through the creation of fire belts in the dry season. Also, some communities (e.g., Tugu) believe that the spirits protect their abode against fire. We observed burnt areas of about two metres around the grove in Tugu, but no sign of burning inside the grove. Burnt woodland and crop fields were burnt in previous years and the year of data collection (2017). Unburnt crop fields and woodlands were particularly selected from communities that have practiced no burning (Nwodua and Katabanawa) for more than 20 years (Andersson et al. 2003). According the respondents in Nwodua, the community occupy relatively small land area thus is not able to practice land fallow or shifting cultivation. So, their forefathers decided on a no burn bye-law to conserve their arable lands. The farm stubble which is burnt in other communities are rather ploughed in to the farmlands for the next rainy season. Katabanawa respondents explained that they decided on burn practice when Agricultural extention agents proposed that to them because they community has more marginal land that arable land. The fallows and crop fields are individually managed; sacred groves are communally managed with a spiritual leader, whereas the woodlands are managed mostly by the Forestry Commission and the communities. The characteristics of the sampling sites and land uses are presented in Table 1.

Table 1. Land use and management systems of study sites. Shaded cells represent selected sampled land use in the study communities

District	Fire Frequency	Community	Land use type						Management system
			CB	CuB	Fal	SG	WB	WuB	
Tolon-Kunbungu	Low	Jagriguyilli							Community
		Nwodua							Community
West Gonja	High	Damongo-Agric settlement							Community
		Mognori							State and community Eco-village
West Mamprusi	Moderate	Wungu							State-community
		Kata-Banawa							Community
East Gonja	High	Kpalbe							Community
		Kushini							State and community
Tamale South	Low	Tugu							State and community
Mion	Moderate	Kpligini							State and community

Land use types are denoted by CB = burnt crop fields, CuB= unburnt crop fields, Fal = fallows, SG = sacred groves WB = burnt woodlands, WuB = unburnt woodlands

Community members who were willing, allowed their farms and fallow fields for sampling. The farmers were selected from this group at random and their plots sampled. For woodlands, plots were selected using Standardised Random Table. Three rectangular plots (100 × 150 m) were randomly located 50 m away from the edges of the selected plots. Using pegs and tap measures, five (20 × 20 m) subplots were systematically demarcated in the three rectangular (100 × 150 m) plots by creating the plots 20 m apart from the edges and 40 m apart at top and bottom corners, and one in the centre. The size of the larger plot was determined by the average size of a household farm, which ranged between one and two hectares.

In each subplot, we enumerated and measured individuals of *A. leiocarpa* and *V. paradoxa* of ≥ 10 cm diameter at breast height (dbh) (1.3 m above ground level) and were classified as adult trees. Individual species with dbh < 10 cm were also enumerated and classified as juveniles. Regeneration from seeds and sprouts from cut and burnt stumps were also counted as juveniles (Aleza et al. 2015). A few forked stems were measured by circumference of the stems and halving the total. For trees that forked below 1.3 m the narrowest part below the forked stem were measured (Aleza et al. 2015). Height of each tree was measured using an improvised pole with calibrations up to 3 m long, which was used at the base of each tree and by ocular estimation for trees higher than 3 m. The distance between plots ranged from a hundred metres to a kilometre within communities and on the outskirts of the communities. An average of three land use types were sampled in each community. A total of 90 plots were sampled in the ten communities.

Data analyses

Size class distribution (SCD)

Although the height of each species was measured; stem diameter was used in determining the size class distribution. Height may be affected by fires and other human disturbances such as prunning for fuel wood and pollarding to feed animals in the dry season in communal commons especially woodlands. Stem diameter is an appropriate parameter to use as it is less affected by disturbance (Glèlè Kakaï et al. 2011; Cousins et al. 2014; Aleza et al. 2015; Inoussa et al. 2017).

The stem diameters (sizes) of eight classes were computed to investigate the size class distribution of the two study species. Trees in the middle classes range (10 cm - 30 cm) were divided into classes of 5 cm increment (<10, 10 – 15.9 cm, 16 – 20.9 cm, 21 – 25.9 cm, 26 –

30.9 cm) and the larger trees were divided into three classes of 10 cm increment (31- 40.9, 41 – 50.9, > 51). This was necessary for the delineation of sizes and also to adjust for the decreasing number of individuals in the last two groups (41 – 50.9 cm and > 51cm). The mean densities of the eight size classes of each species across the land use types were estimated.

Population parameters

The relationships between species, dbh, fire frequency (low, moderate and high) districts and land use were examined by a multiple regression analysis. The mean densities for each size class of A. leiocarpa and V. paradoxa were calculated for the different fire frequency districts (Figure 1, Chapter 2 of this thesis) and land use types. Densities of size classes were plotted by histograms to illustrate the structures of each species in the three categorised fire frequency study districts and land use types. A log-linear analysis was performed on the different size classes of both species across the land use types, to compare the observed structure to the theoretical structure (Glèlè Kakaï et al. 2011). The observed distribution of *A. leiocarpa* and *V. paradoxa* in the different land use types were fitted to a 3-parameter Weibull distribution. A Weibull distribution assumes a shape depending on the value of the shape parameter:

$$f(x) = \frac{c}{b}\left(\frac{x-a}{b}\right) \mathrm{c} - 1 \ \mathrm{exp}\left[-\left(\frac{x-a}{b}\right) c\right]$$

Where x = tree diameter; a = 2 cm - the diameter threshold for individuals in the inventory; b = is the scale parameter for the central value of diameters and c = shape parameter of the structure (Glèlè Kakaï et al. 2011).

Structural parameters of A. leiocarpa and V. paradoxa in all the land use types were estimated. The mean diameter (D in centimetres) was also computed.

Basal area (G), i.e., the sum of the cross-sectional area at 1.3 m above ground level of all trees in a plot was expressed in m2 /ha (van Laar and Akca 2007):

$$G = \frac{\pi}{4}\sum_{i=0}^{n} 0.0001di^2$$

di is the diameter of the ith tree of the plot; = 0.04 ha.

Lorey's mean height was also determined, by multiplying each tree height (h) by its basal area and dividing the sum of this calculation by stand basal area (Philip, 2002):

$$\mathrm{HL} = \frac{\sum_{i=1}^{n} g_i h_i}{\sum_{i=1}^{n} g_i} \ with \ gi = \frac{\pi}{4} di^2$$

gi is the basal area and hi is the height of the ith tree.

ANOVA was used to compare the mean diameter of the two species (A. leiocarpa and V. paradoxa) in the fire frequency districts and six land use types. Data on dbh, height and mean density of adults and juveniles of each species were log-transformed to fit the assumptions of using ANOVA (normality and equality of variances). All analyses were followed by Tukey's multiple range tests to detect the difference between land use types and structural parameters. Data analyses were done using R version 3.4.2 and Rcmdr Plugin EZR (Fox and Bouchet-Valat 2018). Simpson's index of dominance was used to measure the probability that the distribution of the size classes of each species randomly selected is even, and also determine the population stability of the species (Wiegand et al. 2000; Martins and Shackleton, 2017). The equation for Simpson's index of dominance:

$$S = 1/N(N-1)\sum_{i=1}^{8} Ni(Ni-1)$$

N is the total number of stems, Ni is the number of stems in class i, (8) is the number of size classes.

Results

Size class distribution of *Vitellaria paradoxa* and *A. leiocarpa* in low, moderate and high fire frequency districts

The regression analysis to examine the relationship between species, fire frequency, dbh and land use predicted a statistically significant relationship at $R^2 = 0.12$, $F(2, 1310) = 100.95$, $p < 0.001$. Although land use was significant, it contributed negatively to the model (Table 2).

Table 2. Multiple regression coefficients for the relationships between species fire frequency districts, diameter and land use

Variable	Unstandardized Coefficients		Standardised Coefficients	t	Sig.	R2	F-ratio	p	SEE	N
	B	Std. Error	Beta							
Species (Constant)	1.361	0.045		28.00	0.001	0.12	100.96	0.000	0.46	1310
Fire frequency district	0.203	0.000	0.29	12.05	0.001					
Land use	-0.076	0.006	-0.30	-12.37	0.001					

There were significant differences in the densities ($F_{2, 1310} = 2.03$ $p < 0.0001$) and dbh ($F_{2, 1322} = 4.5$ $p < 0.01$) of *V. paradoxa* and *A. leiocarpa* stems across low, moderate and fire frequency districts. The highest tree densities for *A. leiocarpa* (207±9.5 stems/ha) and *V. paradoxa* (241±4.7 stems/ha) were observed in low and high fire frequency districts, respectively. The lowest densities for species were observed in the moderate fire frequency districts. Juvenile densities were also abundant in low and high fire districts for *A. leiocarpa* and *V. paradoxa*, respectively. The highest mean diameters for *A. leiocarpa* (27.2 ±17.5 cm) and *V. paradoxa* (30.5±58.7 cm) were observed in moderate fire districts. There was, however, no significant differences in basal area for both species across the fire frequency districts (Table 3).

Table 3. Structural parameters of *A. leiocarpa* and *V. paradoxa* (mean ± standard deviation) in low moderate and high fire frequency districts. Tukey's honestly Significant difference ($p < 0.05$)

Variables	Species	Fire Frequency districts			
		Low	Moderate	High	p Value
Basal area (m^2 /ha)	*A. leiocarpa*	0.07±0.5	0.01±02	0.23±.001	$F_{2,1320}$ =1, $p > 0.189$
	V. paradoxa	0.08±0.10^b	0.08 ±0.41^b	0.01±0.05^a	
Mean density (adult trees stem/ha)	*A. leiocarpa*	207±9.5$_c$	89.3±10.3^b	14.2±2.5^a	$F_{2, 1310} = 2$, $p < 0.001$
	V. paradoxa	50.7±9.7^a	58.8±30.5^b	241±4.7^c	
Mean density juveniles (stems/ha)	*A. leiocarpa*	90±23.7^c	6.6±2.4^b	2.2±0.02^a	$F_{2,425} = 1$, $p > 0.46$
	V. paradoxa	13.9±0.73^b	10.2±3.5^a	49.2±13.8^c	
Mean diameter (cm)	*A. leiocarpa*	16.2± 24.8^a	27.2 ±17.5^c	24. 2± 10.8^b	$F_{2,1320} = 4$, $p < 0.012$
	V. paradoxa	26.8 ±14.8^b	30.5 ±58.7^c	24.0 ±29.0^a	
Dominance	*A. leiocarpa*	0.03	0.02	0.03	$F_{2,5} = 203$, $p < 0.001$
	V. paradoxa	0.01	0.01	0.02	
Simpson Diversity Index	*A. leiocarpa*	0.72	0.81	0.8	$F_{2,5} = 482$, $p < 0.001$
	V. paradoxa	0.9	0.9	0.8	

Significant differences were observed between species and fire frequency districts ($F_{2, 1322}$ = 270.86 $p < 0.0001$. There were relatively higher numbers of individuals in the lower to middle diameter classes (≤ 10 and ≤ 26 cm) for both species in the three fire frequency districts. Thus, size class distribution for *A. leiocarpa* in the three fire frequency districts was positively skewed in low fire frequency district, and bell-shaped for moderate and high frequency districts. *Vitellaria paradoxa* on the hand, showed a positively skewed distribution in high fire frequency districts and a negatively skewed bell-shaped distribution for moderate fire districts, and almost flat in low fire districts (Figure 3 A and B).

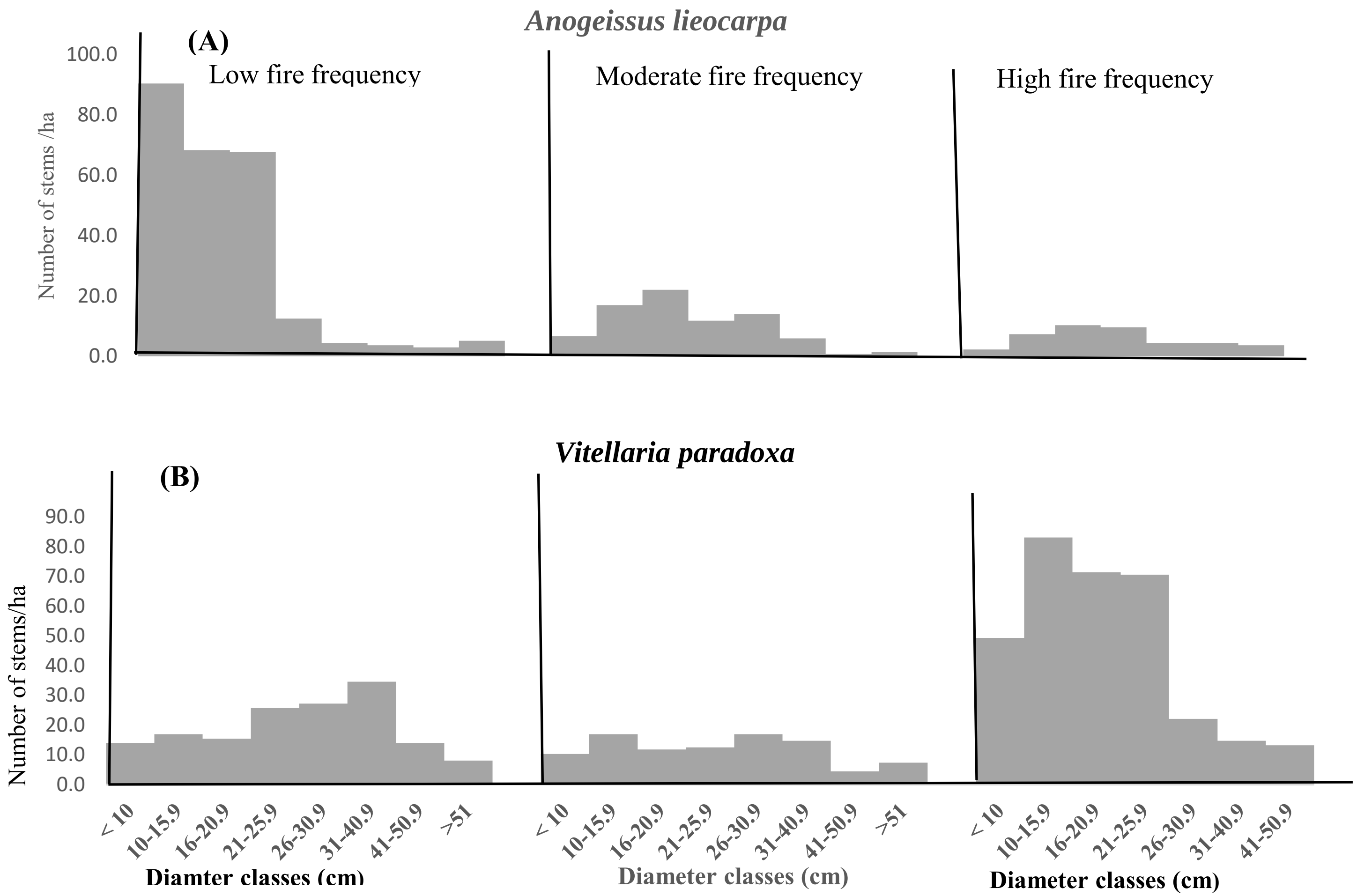

Figure 3. Diameter distribution of (A) *A. leiocarpa* and (B) *V. paradoxa* in the three-fire frequency districts.

Number of plots per frequency district (n) - Low =30, Moderate = 24, High=26

Size class distribution of Vitellaria paradoxa and A. leiocarpa in six land uses

The mean diameter size classes showed significant differences between and within species across all the land use types ($F_{5, 1310} = 23.01$ $p < 0.001$). Similar to the trend observed in fire frequency districts, there were relatively higher numbers of individuals in the lower to middle diameter classes (<10 and <26 cm) for four land uses (sacred groves, burnt and unburnt woodlands, burnt crop fields, unburnt crop field and fallows). *Anogeissus leiocarpa h*ad few or no stems in the larger diameter classes (> 26 cm) in burnt crop fields, unburnt crop fields and fallows (Table 2). *Vitellaria paradoxa,* on the other hand, had a high density in all the diameter classes across all the land use types. The means of *A. leiocarpa* and *V. paradoxa* across the six land use types are presented in Table 2.

Table 4. Densities of diameter classes (mean ± standard deviation) of *A. leiocarpa* and *V. paradoxa* in the six land use types. Significant differences ($p < 0.05$) between land use types

Size class	Species	Land use type						Statistical Parameters Spp * LUT
		CB	CuB	Fal	SG	WB	WuB	
Juveniles (<10cm)	*A. leiocarpa*	0.1 ± 0.1[a]	0.6 ± 0.1[a]	0	78.7 ± 4.4[b]	311 ± 24.0[c]	47.1 ± 5.6[b]	$F_{5, 1791} = 4.7$, $p = 0.003$
	V. paradoxa	12.5 ±2.5[a]	28.5± 2.5[b]	13.2 ±1.4[ab]	45.00±2.8[c]	59.3 ± 6.4[d]	0	
10 – 15.9 cm	*A. leiocarpa*	0	3.9 ± 0.8[a]	0	104 ± 11.7[d]	18.6 ± 1.0[ab]	29 ± 4.0[c]	$F_{5, 66} = 3.5$, $p = 0.004$
	V. paradoxa	2.0 ± 0.3a	10.3 ± 1.2[ab]	20.6 ± 0.8[c]	36.0 ± 2.0[c]	21.4 ± 1.7[b]	89.0 ± 8.0[ab]	
16 – 20.9 cm	*A. leiocarpa*	0.2 ± 0.1a	0	52.2 ± 2.5[d]	2.1 ± 0.3[a]	10 ± 0.9[b]	15.5 ± 1.10[c]	$F_{5, 34} = 8.5$, $p = 0.001$
	V. paradoxa	7.0 ± 0.5a	15.7 ± 1.0[b]	20.5 ± 1.0[c]	19.5 ± 1.6[bc]	11.4 ± 0.8[ab]	5.5 ± 0.6[a]	
21 – 25.9 cm	*A. leiocarpa*	0	0	0	15.5 ± 1.0[c]	13.6 ± 0.6[a]	9.5 ± 1.0b[c]	$F_{5, 8} = 2$, $p = 0.02$
	V. paradoxa	10.2 ± 0.7[ab]	18.5 ± 1.0[c]	35.3 ± 2.4[d]	9.6 ± 0.8[a]	17.0 ± 1.2[c]	12.0 ± 0.8[b]	
26 – 30.9 cm	*A. leiocarpa*	0	0	0	15.5 ± 0.3[ab]	3.6 ± 0.3[a]	9.5 ± 0.8[b]	$F_{5, 8} = 6$, $p = 0.001$
	V. paradoxa	11.9 ± 0.8[b]	15.2 ± 1.0[c]	6.3 ± 0.3[a]	4.3 ± 0.6[a]	6.3 ± 0.5[ab]	4.5 ± 0.4a	
31- 40.9 cm	*A. leiocarpa*	0	0	0	3.7 ± 0.4[b]	0.7 ± 0.2[a]	3.0 ± 0.5[b]	$F_{5, 8} = 8$, $p = 0.001$
	V. paradoxa	19 ± 1.5[b]	10.8 ± 1.0[ab]	5.0 ± 0.4[a]	2.9 ± 0.1[a]	5.6 ±0.5[a]	5.0 ± 0.5[a]	
41 – 50.9 cm	*A. leiocarpa*	0	0	0	0	0.0 ± 0.2[a]	0.1 ± 0.4[b]	$F_{5, 2} = 3$, $p = 0.01$
	V. paradoxa	5.6 ± 0.5[ab]	6.4 ± 0.5[b]	7.5 ± 0.4[ab]	0.7 ± 0.2[a]	0.7 ± 0.2[a]	3.0 ± 0.6[b]	
>51	*A. leiocarpa*	0	0	0	6.6 ± 1.0[b]	0.4 ± 0.1[a]	-	$F_{5,6} = 5$, $p = 0.002$
	V. paradoxa	15 ± 1.0[c]	2.0 ± 0.3[a]	7.5 ± 0.4[b]	2.2 ± 0.3[a]	4.2 ± 1.0[a]	2.5 ± 0.3[a]	

Tukey's honestly Significant difference ($p < 0.05$). Land use types are denoted by SG = Sacred groves CuB= unburnt crop fields, WB = burnt woodland, WuB = unburnt woodland, Number of plots per land use type (n) - CuB =15, CB=21, SG=15, WB=23 and WuB = 17.

Structural parameters of *A. leiocarpa and V. paradoxa* in the six land use types

The basal area for both species varied significantly across the land use types ($F_{5, 1310} = 57.01$ $p < 0.001$). The highest basal area for *A. leiocarpa* (16.9 m^2 /ha) and *V. paradoxa* (20.6 m2/ha) was in sacred groves and unburnt woodland, respectively. The mean density of *A. leiocarpa* in sacred groves was significantly higher ($p = 0.0001$) than unburnt crop fields ($p = 0.02$). Fallows and burnt crop fields had no trees. The mean density of adult *V. paradoxa*, on the other hand, was highest in fallows (15.3±2.2 stems/ha) and was significantly ($p = 0.001$) higher than found in unburnt woodland (6.8±6.6 stems/ha).

Furthermore, the mean density of juveniles of *A. leiocarpa* also varied across the land use types ($p < 0.001$). The mean density of juveniles of *A. leiocarpa* in unburnt woodlands was higher than the mean density of juveniles in unburnt crop fields. The juveniles of *V. paradoxa* in sacred groves also differed markedly ($p = 0.001$) from fallows, burnt and unburnt crop fields ($p = 0.01$). The highest mean diameter of *A. leiocarpa* in unburnt woodlands (23.3±10 cm) was significantly higher ($p = 0.003$) than that found in sacred groves ($p = 0.05$), which had the lowest mean diameter (21.4±30 cm).

The mean diameter of *V. paradoxa* was significantly high in burnt crop fields (36.9±15.5 cm) than unburnt crop fields, burnt and unburnt woodland, fallows, and sacred groves ($p < 0.001$). The mean diameter of V. paradoxa in burnt crop fields was two times higher than the mean diameter estimated in sacred groves (18.2±9.4 cm). Except for *V. paradoxa* in burnt and unburnt crop fields which showed a dominance index (Simpson) of less than 0.1, the occurrence of both species in all other land use types showed a dominance index above 0.1 which indicated that size classes of species population in the other land use types were unevenly distributed (Table 3).

Table 3. Structural parameters of *Anogeissus leiocarpa* and *Vitellaria paradoxa* (mean ± standard deviation) in six land use Tukey's honestly Significant difference ($P < 0.05$).

Variables	Species	Land use type						
		CB	CuB	FAL	SG	WB	WuB	p Value
Basal area (m^2 /ha)	*A. leiocarpa*	-	0.2^{a}	-	16.9^{c}	1.6^{ab}	2.0^{b}	$F_{5, 1310} = 57$ $p < 0.001$
	V. paradoxa	8.6b	5.8^{ab}	2.5^{a}	12.7	13.9^{c}	20.6^{d}	
Mean density (adult trees stem/ha)	*A. leiocarpa*	-	0.8 ± 1.0^{a}	-	22.7 ± 29.7^{c}	2.5 ± 3.5^{ab}	8.85±3.8^{b}	$F_{5\ 746}= 44$, $p > 0.001$)
	V. paradoxa	12.1 ± 6.1^{b}	11.6 ± 4.5^{b}	15.3 ± 2.2^{c}	10.8 ± 14.4^{ab}	9.6 ± 8.2^{ab}	6.8±6.6^{a}	
Mean density juveniles (stems/ha)	*A. leiocarpa*	2.7 ± 1.7^{b}	0.7 ± 0.4^{a}	6.6 ± 9.4^{ab}	86.7 ± 27.0^{cd}	33.6 ± 19.2^{c}	248.0±89.1^{d}	$F_{5, 564} = 11$, $p= 0.003$
	V. paradoxa	9.4 ± 4.6^{a}	25.3 ± 5.7^{b}	5.9 ± 8.3^{a}	26.5 ± 9.3^{b}	47.1 ± 17.2^{bc}	68.0±29.7^{c}	
Mean diameter (cm)	*A. leiocarpa*	-	22.7 ± 11.9^{ab}	-	21.4 ± 30.1^{a}	22.3± 18.0^{ab}	23.3±10.1^{b}	$F_{5, 1310} = 23$ $p < 0.001$
	V. paradoxa	36.9 ± 15.5^{d}	27.9 ± 13.1^{b}	30.2 ± 17.9^{c}	18.3 ± 9.4^{a}	27.7 ± 37.2^{b}	29.1±61.7^{c}	
SCD Weibull (c-value)	*A. leiocarpa*	-	3.0	-	1.1	1.07	2.1	
	V. paradoxa	2.3	2.7	1.5	1.7	1.0	1.1	$F_{2,5} = 203$, $p < 0.001$
Simpson's Index of Dominance	*A. leiocarpa*	0.9	1.0	1.0	0.5	0.9	0.4	
	V. paradoxa	0.1	0.0	0.2	0.9	0.6	0.9	$F_{2,5} = 482$, $p < 0.001$

Tukey's Honestly Significant difference ($P < 0.05$). Land use types are denoted by SG = Sacred groves CuB= unburnt crop fields, WB = burnt woodland, WuB = unburnt woodland, Number of plots per land use type (n) - CuB =15, CB=21, SG=15, WB=23 and WuB = 17.

Structures of *V. paradoxa* and *A. leiocarpa* in the six land use types

Generally, all the size classes across the six land use types fitted well to the Weibull distribution ($p < 0.001$). However, the distribution of *A. leiocarpa* and *V. paradoxa* in sacred groves, fallows (only *V. paradoxa*), unburnt crop fields, burnt and unburnt woodlands were more positively skewed than burnt crop fields with *A. leiocarpa* absent in burnt crop fields and fallows.

The classes of *V. paradoxa* in burnt woodland, unburnt woodland and sacred groves showed a Weibull c = 0.9 in burnt woodlands ($\chi 2 = 157.44$ df = 7, $p < 0.0001$), c = 1 in unburnt woodland ($\chi^2 = 65.69$, df = 7, $p < 0.001$) and c = 1 for sacred groves ($\chi 2 = 115.69$, df = 7, $p < 0.001$), respectively. Burnt woodlands and sacred groves showed a near inverse J shape distribution but quite pronounced in burnt woodlands. Both land uses exhibited a relative dominance of individuals within the size class range of ≤ 10 to 26 cm and ≤ 10 to 21cm for burnt woodland and sacred grove, respectively.

Although fallows had very few individuals in juvenile and mid-size classes (16-21 cm, 21-26 cm) the distribution exhibits a positive asymmetry. *Vitellaria. paradoxa* showed a bell-shaped distribution ($1 < c < 3.6$) in crop fields. Both burnt and unburnt crop fields showed asymmetric distributions - a characteristic of stands with a lower number of individuals in juvenile size classes, dominated by individuals in mid-classes (10-21 cm, 21-31) and larger individuals within the size class range of 31cm to ≥ 50cm. Thus, *Vitellaria paradoxa* in crop fields had a high prevalence of individuals in size class range of 20 - > 50 cm than small diameter size classes (≤ 10 cm) (Fig 3). Unburnt crop fields showed a more balanced distribution within the middle classes compared to burnt crop field which mimicked a negative assymetric distribution with relatively high number of individuals in large diameter classes (41-50 cm).

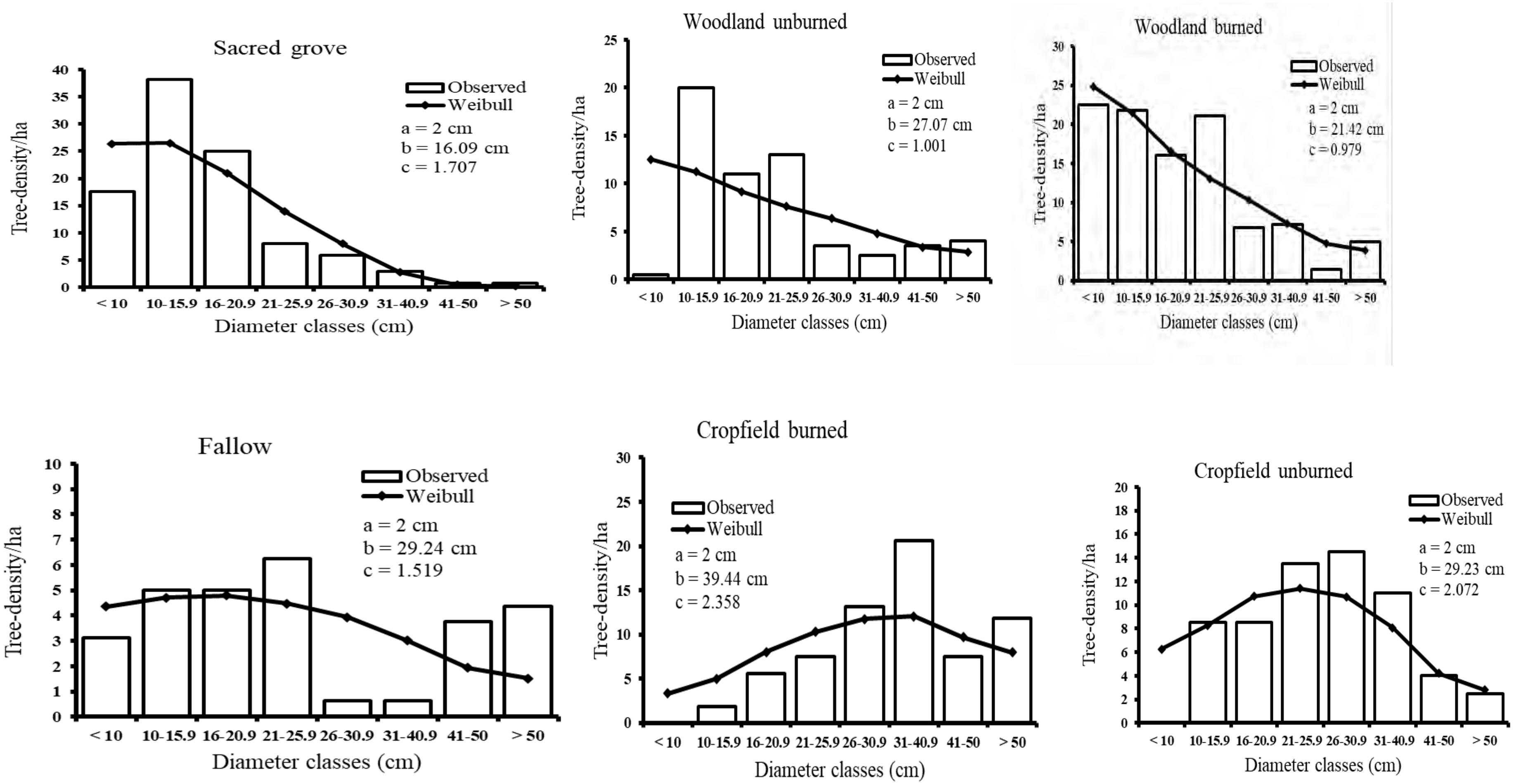

Figure 3: Diameter distribution of *V. paradoxa* in the six land use types. Land use types are denoted by SG = Sacred groves CuB= unburnt crop fields, WB = burnt woodland, WuB = unburnt woodland. Number of plots per land use type (n) – C
uB =15, CB=21, SG=15, WB=23 and WuB = 17.

The observed and theoretical distributions of *A. leiocarpa* showed a distribution of small numbers of juveniles and an increase in the immediate class (10-16 cm) while progressively decreasing in the subsequent classes. Thus, assuming a somewhat inverse J-shape distribution with a Weibull of c = 1 in burnt woodland ($\chi^2 = 112.7$, df = 7, $p < 0.001$), (c = 1) in sacred groves ($\chi^2 = 263.6$, df = 7, $p < 0.001$) and exhibited an uneven-aged population in these land use types. The number of *Anogeissus leiocarpa* in unburnt woodland was relatively low in the juvenile class but showed a comparatively high distribution of mid-diameter classes of 10-16 cm and 16-21 cm, with descending frequencies in the larger diameter classes, thus, exhibiting a positive asymmetric distribution with a Weibull c = 2. The diameter class distribution was also significantly different ($\chi2 = 43.5$, df = 7, $p > 0.001$) (Fig. 4). *Anogeissus leiocarpa* was, however, absent in burnt crop fields and fallows.

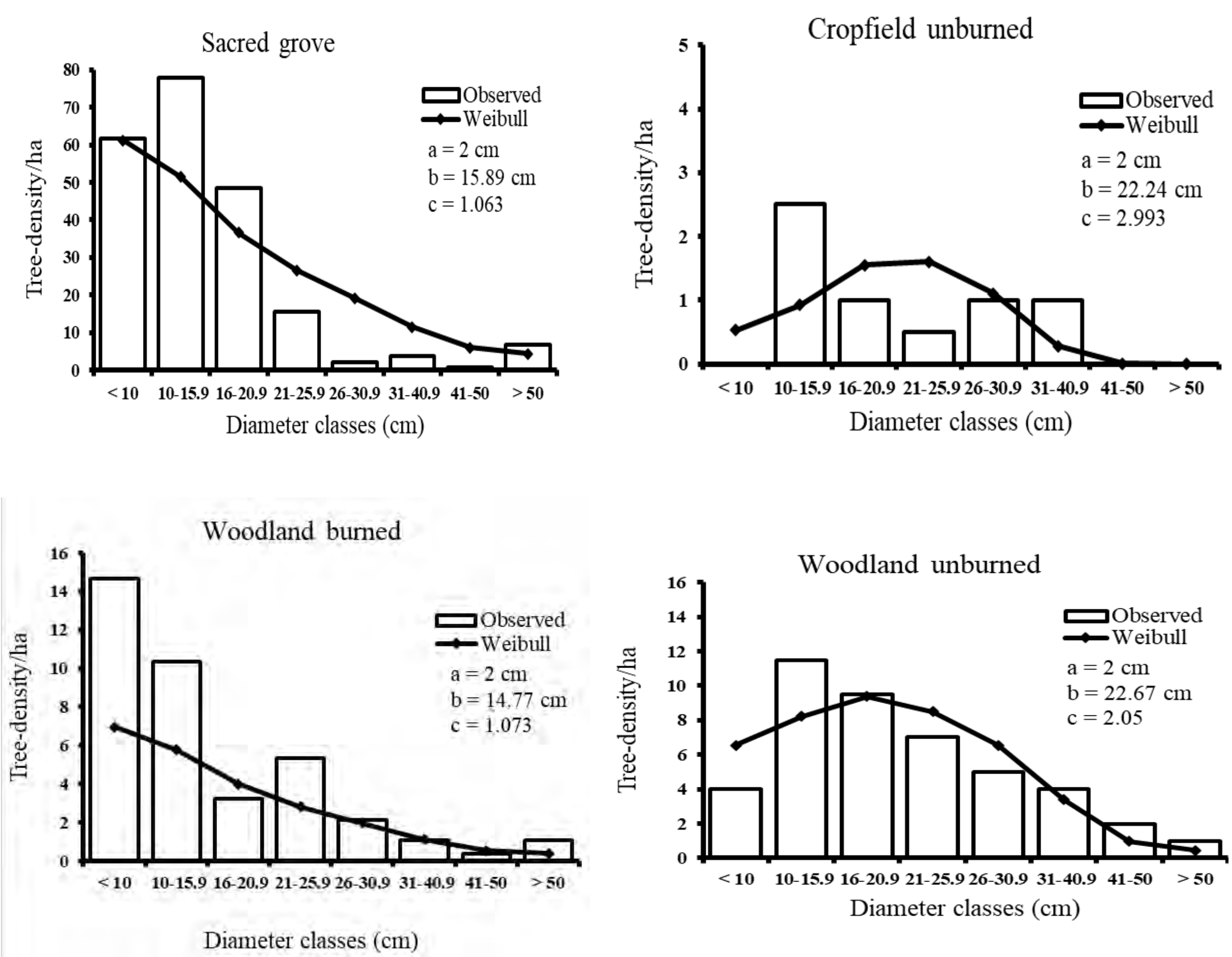

Figure 4: Diameter distribution of *A. leiocarpa* in the four land use types. Land use types are denoted by SG = Sacred

groves CuB= unburnt crop fields, WB = burnt woodland, WuB = unburnt woodland, Number of plots per land use type (n) - CuB =15, CB=21, SG=15, WB=23 and WuB = 17.

Discussion

Population and structural parameters of *A. leiocarpa* and *V. paradoxa* in three fire frequency districts and six land use types

The regression analysis showed that fire frequency has an effect on the populations and structure of both species as well as the SCD of species. Species population dynamics, is thus, affected by fire frequency and land use as observed in this study.

The relatively high number of stems of *V. paradoxa* and *A. leiocarpa* in the low to middle diameter size classes (< 10 and ≤ 21 cm) found in all the fire frequency districts, is an indication of continuous recruitment of both species in this fire prone area (Guinea savanna). Just as found in the Chapter 3 of this thesis, some species are affiliated to no-burn and burnt treatments thereby recording high relative number of stems in the respective treatments. In Chapter 3, species were found in relatively high frequencies in no-burn plots, and this Chapter also reports that *A. leiocarpa* was found in abundance in sacred groves and woodlands with little fire on no fire. In contrast, *V. paradoxa* which recorded high number of stems in the no-burn treatment (Chapter 3) is abundant in high fire frequency districts. So, the dynamics of recruitment and survival of *V. paradoxa* is not clear in terms of the species response to fire or no-fire. The high density in high fire frequency districts and in no-burn treatment (Chapter 3) could however be attributed to the easy adaptation of the species to these fire regimes (Lykke 1998).

The high density of *V. paradoxa* in both burnt and unburnt land use types than *A. leiocarpa* in crop fields and fallows, is an indication that fire use for cropping affects the regeneration and recruitment of both species. This is because at the seedling stage, stem height and diameter rarely escape fire effects (Lykke 1998). Schumann et al. (2011) and Aleza et al. (2015) found high regeneration and recruitment of both species in crop fields and fallows in Burkina Faso and Benin, respectively and which might be attributed to the fire regime and to a large extent crop management practice which differ amongst farmers. The decline in the number of *A. leiocarpa* in the successive diameter classes (> 21-26 cm) in crop fields and fallows is an indication of high mortality of the species and non-protection during the regenerative and establishment stages compared to *V.*

paradoxa in crop fields. This is attributed to a high preference (Blench 2001; Djossa et al. 2008; Schumann et al. 2011) for *V. paradoxa* in crop fields over *A. leiocarpa*, thus less protection of *A. leiocarpa* from fire and cropping. The reduction in the population of *A. leiocarpa* in burnt land use types can possibly be attributed to its sensitivity to fire (Hennenberg et al. 2005; Schumann et al. 2011).

Vitellaria paradoxa exhibited more tolerance to fire than *A. leiocarpa*, which had relatively low basal area and densities in burnt land use types (Hennenberg et al. 2005). This confirms the general characteristics of *V. paradoxa* as a fire tolerant species that can withstand a degree of burning and continue growing despite damage from fire. Adult trees can withstand fire as they have thick, fissured bark and the height of trees aids in escaping fire (Naughton et al. 2015; Osborne et al. 2018).

The basal area of *V. paradoxa* in burnt and unburnt woodlands in this study was 3.5 times higher than that found in a similar study (Lovett and Haq 2000). Also, the basal area for burnt and unburnt crop fields was 2.7 times higher than the estimates of high and medium intensity farmlands in the same study (Lovett and Haq 2000) and by Glew and Lovett 2014. This agrees with Boffa et al.'s (2000) observation in Côte d'Ivoire that the regeneration of *V. paradoxa* is supported because of the valuable nuts. The nuts from *V. paradoxa* are one of the leading non-timber forest products (NTFPs) in the West African sub-region by economic value (Aleza et al. 2015; Naughton et al. 2011). Thus, efforts by communities to protect the species from fire and other forms of disturbance have increased over the years with the growing importance of shea butter at both local and international levels (Glew and Lovett 2014). Fire exclusion and minimum human interference promoted the growth of *V. paradoxa* with relatively high adult tree and juvenile densities across all the land use types.

The mean adult densities of *V. paradoxa* found in this study were within the density range reported in other countries in the Guinea savanna of West Africa (Boffa 1995; Glèlè Kakaï et al. 2011; Aleza et al. 2015). In contrast, the highest mean adult density observed in fallows was much lower than that observed in both old and young fallows by Aleza et al. (2015). The crop management regimes before fallowing, as well as the differences in climatic and edaphic conditions, are possible contributory factors to these differences in densities. *Vitellaria paradoxa* densities in all the land use types were much higher than what was observed in Appiah (2013) in the transitional zone of

Ghana. This is because *V. paradoxa* is more of a savanna species than forest species hence, the high abundance estimated in this study than in the forest-savanna transition zone.

Anogeissus leiocarpa, on the other hand, had a relatively high adult tree density and basal area in sacred groves and rather showed high regeneration in both unburnt and unburnt woodlands. The basal area of *A. leiocarpa* in sacred groves was higher than that found by Inoussa et al. (2017), as what was found in high and low anthropogenic pressure stands in Wari-Maro Forest Reserve in Benin (Assogbadjo et al. 2010).

The relatively low mean density of *Anogeissus leiocarpa* in unburnt crop fields and the total absence in burnt crop fields and fallows shows the vulnerability of the species to fire and pressure from cropping (Schumann et al. 2011). The highest mean densities of adult trees recorded in sacred groves and burnt woodlands were lower than the densities found in high and low-pressure anthropogenic stands in Inoussa et al. (2017). *Anogeissus leiocarpa* is noted to thrive well in much drier environments (Hennenberg et al. 2005), such as the Sudano-Sahelian climate of Southern Niger, resulting in higher abundance than the Sudanian climate of the north of Ghana. Again, the differences are probably due to the large size class range (5 cm – 90 cm) for adult trees in the study which could contribute to the higher densities recorded. This study had a range between 10 cm and > 50 cm with a decreasing number of trees in the last two classes (41-50 cm and > 50 cm). Apart from unburnt crop fields, the mean densities of *A. leiocarpa* in sacred groves, burnt and unburnt woodlands were higher than what was recorded in the transitional zone (Appiah 2013), which could be attributed to the extent of deforestation in the transitional zone as previously outlined by the same authors (Appiah et al. 2009).

For *V. paradoxa*, the mean diameter in our study was much lower than what was recorded in Benin by Aleza et al. (2015). These differences in dbh could be attributed to the degree and history of disturbances at the plot level in the different studies. Trade-offs between growth and survival, which are also dependent soil and climate affect the dbh (Dillon et al. 2019) could also contribute to this difference in mean diameter sizes. Burnt crop fields, which had the lowest density had the highest mean dbh due to the use of annual use of fires so that juveniles are not able to survive over the years.

However, there is anthropic selection of *V. paradoxa* (see Lovett and Haq 2000) in crop fields at the regeneration and recruitment stages which could enhance the growth of *V. paradoxa* in crop fields compared to unmanaged woodlands (Lovett and Haq 2000). This selection and protection of preferred woody species is a traditional practice in the conservation of *V. paradoxa* and other economically valuable species on farmlands is what defines the agroforestry parkland of across West Africa and other African countries like Uganda (Fifanou et al 2011; Gwali et al. 2012).

The high mean density of juveniles of *V. paradoxa* and *A. leiocarpa* in sacred groves and woodland is an indication that the conservation of species by natural regeneration can be achieved by promoting environments with minimum human interference. Contrary to other studies that found higher densities of *A. leiocarpa* in fallows (e.g. Bognounou et al. 2010; Schumann et al. 2011; Jurisch et al. 2012), this study recorded lower densities of regeneration in fallows than woodlands. The intensity of cropping and fire before fallowing could probably contribute to the poor growth and survival of individuals in fallows in our study. A longer fallow period could allow for a higher regeneration.

The mean diameter of *A. leiocarpa* in unburnt woodlands and unburnt crop fields was higher than what was reported in the transitional ecological zone of Ghana (Appiah 2013). The climatic regime in the Guinea savanna of Ghana is unimodal and may be favourable for the growth of the species which may have accounted for the high diameter sizes in the study.

Size class distribution of A. leiocarpa and V. paradoxa in six land use types

Generally, the study revealed that fire frequency and the different land use types influenced the size class distribution of *A. leiocarpa* and *V. paradoxa* (Schumann et al. 2011). The representation of both species in the three fire frequency districts showed reversed structures in low and high fire frequency zones respect. The highest densities and inverse J structures found in the low and high frequency districts for *A. leiocarpa* and *V. paradoxa* is indicative of the sensitive and resistant characteristic of the species respectively. Consistently, *A. leiocarpa* is known to be sensitive to fire (Sobey 1978; Hennenberg et al. 2005). However, *V. paradoxa* which is known to be fire resistant has also been found in relatively high densities in both burnt and unburnt environments. The low densities and SCD found in moderate fire frequency districts, show the slow recruitment and survival of both species in these areas. Cardoso et al. (2016) described species response to fire in the West Africa as winners and losers. These descriptors may well describe the impact of fire frequency on the two species where *A. leiocarpa* loses recruitment and survival in high frequency fire prone areas, but a win for *V. paradoxa* which is presupposed to adapt to both no fire as well as high fire frequency areas. Cardoso et al. (2016) also mentioned that some species, such as *Bombax buonopozense*, thrived well in both forest and savanna areas, as can be observed of *V. paradoxa.* This characteristic of *V. paradoxa* may be contributing to the prevalence of the species in fire prone Guinea savannas of Benin, Burkina Faso, Ghana and Ivory Coast which are the leading exporters of shea butter and kennel (Glew and Lovett 2014).

The structural differences observed in the land use types illustrate the survival of species in burnt and unburnt environments (Hennenberg et al. 2005; Sanogo et al. 2015; Mattana et al. 2018). However, the population structures of both species observed in crop fields cannot be solely attributed to the impact of fire, as there is a growing trend in the use of ploughs in crop fields which also affects the regeneration and survival of individuals (Songsore 1996; Diao et al. 2014). Both *V. paradoxa* and *A. leiocarpa* had near inverse J-shaped SCD in sacred groves, and burnt and unburnt woodlands, which is indicative of healthy and growing population in these land use types, and a desirable indicator for the conservation of species. The near inverse J-shaped distribution observed in sacred groves is a demonstration of the vital role that some cultural practices play in the conservation of species. This confirms findings from other studies which have indicated that sacred groves in Ghana and other parts of the world have contributed to the protection and conservation of species (Schaff and Lee 2005; Ormsby 2012).

The SCD of *A. leiocarpa* in sacred groves is very similar to what was found in a state-protected area by Inoussa et al. (2017). This implies that cultural belief systems could be as effective as conventional conservation methods in the protection of some plant species. Thus, community participation and the incorporation of traditional practices can be beneficial to the management and conservation of species (Gwali et al. 2012; Boafo et al. 2016). Furthermore, the inverse J-shaped distribution of both species found in burnt and unburnt woodlands has a conservation implication that woodlands are still conducive habitats for the conservation of these species.

In contrast, some research findings that indicated *A. leiocarpa* as a fire-sensitive species (Sobey, 1978; Hennenberg et al. 2005), a steeper inverse J-shaped structure was found in burnt woodlands than in unburnt woodlands. Amoako et al. (2018) also found *A. leiocarpa* in late season burning plots at the Mole National Park. The presence of *A. leiocarpa* in burnt land use types is most probably due to the species adaption to the seasonal fires in some of these parklands. This could be a confirmation to the findings that species do adapt to a disturbance regime and may increase in population overtime (Lykke 1998).

The bell-shaped structures found in moderate fire frequency districts and crop fields for *A. leiocarpa* and *V. paradoxa*, is indicative of poor regeneration, recruitment and establishment phases in these districts and land use types. For bell-shaped structures in fallows, a more extended period of rest from cropping and fire, may improve regeneration, since both species are long-lived and populations may be sustained even by low juvenile recruitment rate (Venter and Witkowski 2013).

Conclusion

The study revealed that fire frequency and land use influenced the population structure and abundance of *A. leiocarpa* and *V. paradoxa* both positively and negatively. This was reflected in the differences in basal area and density, as well as the SCD profile of the two species across the fire frequency districts and six land use types. The near inverse J-shaped distributions found in burnt woodlands and sacred groves for *V. paradoxa* and *A. leiocarpa* respectively, is a confirmation of both species ability to regenerate and survive in low and high fire frequency areas.

The differences in the observed and theoretical distributions depict each species' level of tolerance to fire. *Vitellaria paradoxa* seems to thrive in both burnt and unburnt land use types, as it was found to be widespread in all the fire frequency districts and land use types. However, with their sensitivity (*A. leiocarpa*) and tolerance (*V. paradoxa*) characteristics and responses to fire, the respective fire frequency areas and land uses could be a 'safe haven' for the natural regeneration of the species.

The gradual but significant reduction of regeneration of *V. paradoxa* and the total absence of *A. leiocarpa* in burnt crop fields and fallows poses some concern for their conservation. The combination of fire use and ploughing during land preparation for cropping in traditional agroforestry systems, as practiced in the parklands of West Africa, is potentially a threat to the survival of both species. There is therefore a need to engage communities in the management of these economically important species particularly *A. leiocarpa*, which showed a higher sensitivity to both fire and cropping than *V. paradoxa*.

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CHAPTER 5: EFFECTS OF ANTHROPOGENIC FIRES AND FIRE FREQUENCY ON SOME SOIL PROPERTIES IN THE GUINEA SAVANNA ECOLOGICAL ZONE, GHANA

Abstract

Fire is an important factor influencing the structure and function of tropical savannas. In spite of the extensive studies conducted on the effects of fire on soils in protected areas very few have been conducted in the unprotected savannas or the commons. The fires are anthropogenic and mainly caused by hunters and farmers to flush out animals, remove debris from crop fields and to improve soil fertility. We investigated how bush fires influence some soil properties in four land use types in six districts in the Guinea savanna of Ghana. Data on fire counts were obtained from the CSIR Meraka Institute, South Africa, and fire densities calculated for each district. Soils were sampled in burnt and unburnt woodlands and crop fields and analysed for pH, available Phosphorous (P), Total Nitrogen (TN), Soil Organic Carbon (SOC), exchangeable Calcium (Ca) and Magnesium (Mg), Cation Exchange Capacity, Electrical Conductivity and texture. The fire densities varied amongst the selected districts. Of the six districts, the East Gonja district recorded the highest fire density (1.0 fire $km^{-2)}$ and Tamale the lowest density (0.3 fires km^{-2}). High fire frequencies were recorded in districts with high grass fuel loads and abundant wildlife. Total soil N, SOC, pH and exchangeable Ca differed significantly across the different land use types. There was a stronger association and more positive gradient of Total N and SOC in woodlands than in crop fields. Fire aided the mineralisation of TN, SOC and exchangeable Ca as burnt fields had higher mean values of these nutrients than unburnt fields. Further studies are needed to fully understand the importance of fire regimes on soils in the Guinea savanna.

Keywords: bush burning; fire counts; Guinea savanna; land use; soil properties.

Introduction

Savannas constitute about 50% of Africa's terrestrial ecosystems (Osborne 2018). However, studies have shown that the African savannas have undergone transformation through anthropogenic activities including the indiscriminate anthropogenic use of fire (Tarimo et al. 2015; Bond et al. 2016; Dwomoh and Wimberly 2017). A number of researchers (Trollope and Trollope 2002; Andersson et al. 2003: Coetsee et al. 2010; Pricope and Binford 2012; Sluyter and Duvall 2016; Dwomoh and Wimberly 2017) found that there is regular burning of vegetation in Africa savannas. Satellite images and ground truthing confirm a pattern of burning from January to April in West Africa and from July to October in the East and parts of Southern Africa (N'Datchoh et al. 2015; Tarimo et al. 2015; Knowles et al. 2016; Dwomoh and Wimberly 2017). The authors highlighted the extensive and frequent use of fire in African savannas, demonstrating why Africa is referred to as the 'fire continent' (Knowles et al. 2016).

Land use practices, including the use of fire, may have effects on both vegetation and soils (Scholes and Walker, 1993; Van Langevelde et al. 2003). It is noted that soil-fire relationship predominantly defines the structure, function, composition and dynamics of most savanna ecosystems (Bassett and Crummy 2003; van Wilgen 2009; Certini 2014). The relationship between fire and soil nutrients is an interaction among many factors including fire intensity, season, type and frequency which affects post-fire nutrient dynamics (Certini 20014; Santin and Doerr 2016). Fire intensity for instance, has both direct and indirect impacts on many of the mechanisms that affect nutrient pools and cycling. Soil properties are, therefore, fundamental to the sustainability of savannas and all vegetation types and require further monitoring and greater attention than they have received (Basett et al. 2003; Vogt 2015).

Through the combustion of biomass, soil properties are altered and different soils nutrients are influenced differently. For instance, while nutrients, such as nitrogen (N) may be volatised even at low temperatures (200ºC) due to their sensitive temperature threshold, calcium (Ca) is made more available at the same temperature (Nardoto and Bustamante 2003). Thus, in contrast to natural processes, which may require years or in some cases, decades for decomposition to occur, fire is recognised as a rapid mineralising agent of some soil nutrients (Nardoto and Bustamante 2003; Certini 2005; Pivello et al. 2010; Hanan et al. 2017).[3]

Additionally, the removal of vegetation cover during burning exposes the land to various forms of degradation, including erosion, leaching and reduction in soil porosity (Ferreira et al. 2008). Slow infiltration and percolation in soils have also been attributed to the burning of vegetation, which leads to high runoff resulting in the loss of topsoil (Kato and Haridasan 2002). In contrast, temperatures of 200°C are reported to affect soil positively by increasing nutrient availability to plants and thus increasing plant productivity through increased supply of available nitrogen, phosphorus and sulphur for plant growth (Bagamsah 2005; Kugbe et al. 2012; 2014).Thus, the resultant changes in soil composition and processes after fires are very dependent on the fire regime (Sanin and Doerr 2016).

The study of fire effects on soils in fire-adapted Sudano-Guinean savanna parklands (which cover approximately 1.3 million km2 (35%) of the total West African region) is therefore important. There are a number of studies (Andersson et al. 2003; N'Datchoh et al. 2015; Cardoso 2016; Amoako et al. 2018) on how biomass burning influences vegetation in these savannas and parklands. However, only a few studies have been conducted on how the multiple uses of fire influence fire occurrences and the effects on soils in these savannas. For instance, fire use in the agroforestry parklands of West Africa is mainly for traditional livelihood activities such as land preparation for cropping, hunting, honey harvesting, clearing around homesteads.

As mentioned in the Introductory Chapter of this thesis, it is important to ascertain the impacts of the myriad uses of fire around the world and West Africa in particular on soil in this region. Kugbe et al. (2012, 2014) investigated seasonal burns and the impact of nutrient loss, and found that

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[3] **Amoako, E. E.** and Gambiza, J. (2019) . Effects of anthropogenic fires on soil properties and the implications of fire frequency for the Guinea savanna ecological zone, Ghana, Scientific African, 6(2019), 11. doi: 10.1016/j.sciaf.2019.e00201

temporal loss of phosphorous in the soil after burning could be a threat to the sustenance of the ecosystem in the long term. N'Datchoh et al. (2015) studied the interaction between climate-related and anthropogenic fire regimes. The study showed that people set fires when the climate conditions allowed for vegetation to burn. Bagamsah (2005) investigated the impact of burning on both vegetation and soil in the Guinea savanna woodland and parkland of Ghana and concluded that nutrient status is very low and the structure of the soil is poor. Again, the study showed that fuel load is mainly influenced by the structure of the vegetation cover. Pyne (2003) considered the use of fire in agriculture, and the names attributed to the various occasions that fire is used within the cropping season in the southern part of Ghana and also proposed ways of protecting forest reserves from wildfires in Ghana.The few studies conducted on savanna fires in Ghana have indicated that biomass burning, particularly in the dry season, has been an annual event in the Northern Region of Ghana for decades, with records dating back to colonial times (Korem 1985; Pyne 2003; Andersson et al. 2003; Bagamsah 2005; Kugbe et al. 2012, 2014). The studies argue that bushfires are due to the uncontrolled use of fire for hunting, charcoal production, and crop production (pre-cropping and post-harvest), as most farmers in the north of Ghana use fire for land preparation for cropping (Andersson et al. 2003; Bagamsah 2005; Kugbe et al. 2012, 2014; Pyne 2003). Korem (1985) also reported that fires frequently occur in areas with large populations of game and livestock and indicated that the effect of fire on natural pastures and parklands in the savanna is enormous.

Kugbe et al. (2012) estimated that 37±2.6 thousand km^2 (46–60 %) of the Guinea savanna of Ghana are annually burnt during the dry season. It is well documented (e.g., Gyasi et al. 1995; Dwomoh and Wimberly 2017) that fire-assisted land use practices are fundamental to livelihood diversification in the region. For instance, charcoal burning and honey harvesting are increasingly becoming alternative sources of rural livelihoods as crops fail with the changing climates. Thus, the seasonal fires may be a threat to woodlands and parklands in which these livelihood activities occur. In this paper, we hypothesised that anthropogenic fires could influence soils differently in different land uses in the Guinea savanna. We therefore assessed the effects of fire on soil chemical and physical properties in burnt and unburnt crop fields and woodlands. Thus, data presented here answered two questions: 1. How does fire influence soils in burnt crop fields and woodlands in the Guinea savanna? 2. What are the implications of burning and no-burning for the study districts and communities?

Methodology

Study area

The study was conducted in the Guinea savanna of Northern Region, Ghana (9.5439° N, 0.9057° W) with a population density of 35 persons km^{-2} (Ghana Statistical Service 2012). The region has an average altitude of 150 m above sea level with undulating topography. Geologically, the soils develop from a Voltaian sandstone and consist of laterites, with a silty to sandy loam texture. The soils are inherently low in organic matter, friable, moderately acidic, with thin top soils (<20 cm) which are prone to erosion. In some areas there are iron concretions a few centimetres below the surface of the soil (Vanlauwe 2002; Braimoh and Vlek 2008). These soils are locally characterised as savanna Ochrosols (Obeng 1956; Brammer 1962) ranging from black, alluvial soils and brown, salty soils, to stony/gravelly soils and are classified as Luvisols and Fluvisols in the World Reference Base for Soil Resources (Mikkelsen and Langohr, 2004).

The climate is tropical with long dry spells between November and April. The region has a unimodal rainfall distribution with an annual mean of 1,100 mm. The peak of the rainy season ranges from July to September. Thus, the region has only one cropping season. Rainfall exceeds potential evaporation occurring within a relatively short period of three to four months (Kranjac-Berisavljevic et al. 1999).

The mean annual temperature is 29°C. The annual potential open-water evaporation in the north of Ghana is 2,000 mm (FAO 2005). The region has a dry climate due to its proximity to the Sahel and experiences north-easterly winds (Harmattan) between November and April which facilitates vegetation burning (Kranjac-Berisavljevic et al. 1999).

The region occupies about 62% of the Guinea savanna ecological zone (147,900 km^{2}) of Ghana (Raamsdonk et al. 2008). It is characterised by fire and drought-resistant woody species such as *Combretum* spp, *Vitellaria paradoxa*, *Burkea africana* and *Isoberlinia doka* with common grasses such as *Andropogon*, *Heteropogon* and *Hyparrhenia* spp. A third of natural pastures (71% of 235 000 km^{2}) in the country fall within this region (Raamsdonk et al. 2008) (Fig.1).

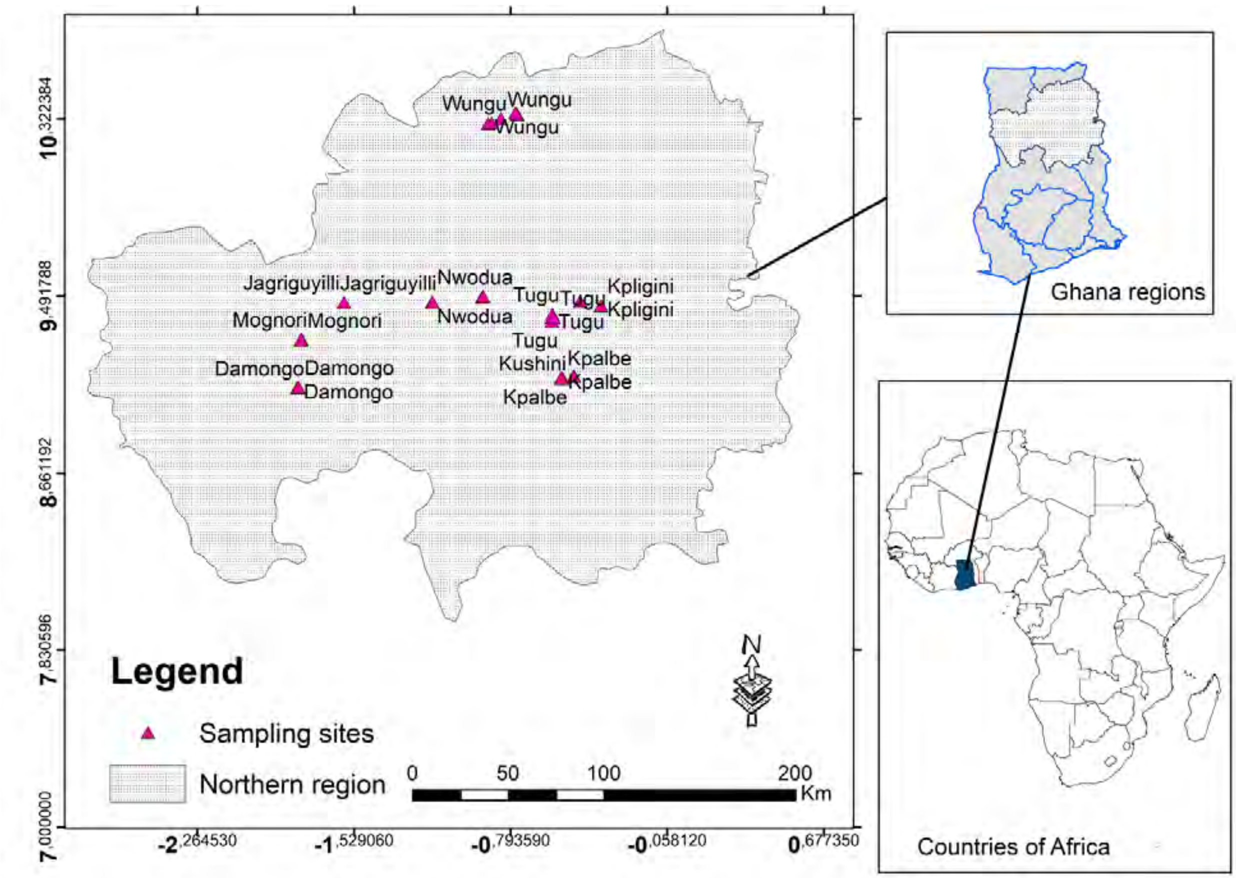


Figure 1. Study area showing sampling sites

Farming is the predominant occupation in Ghana. Agriculture is practised on a small scale, with a farm-family cultivating one or more farm holdings of one to two hectares each (Gyasi et al. 1995). Farmers typically grow crops and keep animals: ruminants and poultry. Both land and crop rotation are commonly practised in the region, and grass in the crop fields is burnt, as part of land preparation before the soil is ploughed and hoed. The burning is done early (December to end January) or late in the dry season (February to April) depending on the type of crop to be cultivated. Some fields may be burnt twice to get rid of any debris from the previous burn.

Fire count data and selection of study sites

Data on daily fire counts (detected by sensors on Earth observation satellite) from 2013 to 2017 in Ghana, were received from the Advanced Fire Information System (CSIR, Meraka Institute), South Africa and the EORIC (Earth Observation Research and Innovation Centre), Ghana. Fire densities were calculated for 18 districts in the Northern region and the districts stratified into high

(> 0.5 fires km^{-2}) and low (< 0.5 fires km^{-2}) zones. Of the 18 districts, six districts (Three districts in each zone) and ten communities (five communities in each zone) were purposively sampled in the stratified fire count zones with the assistance of the regional office of the Ghana Forestry Commission. Purposive sampling (Lavrakas 2008) was necessary to include the few communities that practice no-burning and also due to financial constraints.

Community leaders were contacted to assist in the selection of sampling sites. Most of the unburnt crop fields and woodlands were selected from two communities (Nwodua and Katabanawa) that have practised no burning for more than 20 years (Andersson et al. 2003). Also, two communities (Jagriguyilli – UNESCO Heritage site, and Tugu) where portions of woodlands have been protected from fire and other human activities (sacred groves) by the communities for several decades, were sampled. In the remaining six communities, we selected fire using (for land preparation before and /or after harvest) and non-fire using households. Burnt crop fields and woodlands were burnt in previous dry seasons and the year of data collection (2017). The burnt and unburnt land use types are hereinafter referred to as burnt and unburnt crop fields and woodlands.

Depending on the extent of the land use types, a minimum of two and a maximum of four land use types were sample. Tugu, Jagriguyilli, Kpalbe and Kushini communities had more than two land use types with a higher number of sites for sampling than the remaining communities which accounted for the unequal number of plots per community. The distance between sampling sites within communities varied from 1 to 3 km in all communities, while the distance between selected communities in the respective districts varied between 10 and 30 km. Some characteristics of the selected districts and communities are presented in Table 1.

Table 1. Geographic, demographic characteristics fire density and sampled land-use types of selected communities and districts

Community	District/municipal	Land area (km²)	Household in agricul-ture (%)	Fire density (km²)	Land use type sampled
Tugu	Tamale (9.4034°N,0.8424° W)	731	26	0.3	Burnt woodlands, unburnt woodlands, burnt crop fields
Jagriguyilli and Nwodua	Tolon-Kumbungu (9.4310°N, 1.0649°W)	2,389	96	0.4	Unburnt woodlands, unburnt crop field and burnt crop fields
Wungu and Katabanawa	West Mamprusi (10.352°N, 0.799°W)	4,892	85	0.4	Burnt and unburnt woodlands, burnt unburnt crop fields
Kpligini	Mion (9.4450°N,0.0093° W)	4,160	92	0.6	Burnt woodlands, burnt crop fields
Damongo-Agric and Mognori	West Gonja 9.084°N, 1.818°W	17,317	82	0.7	Burnt and unburnt woodlands, burnt crop fields
Kushini and Kpalbe	East Gonja (8.5509°N 0.5183°W)	9,351	76	1	Burnt woodlands, burnt and unburnt crop fields

Source: Ghana Statistical Service (2012) and field data (2017)

Sampling design and laboratory analyses

A total of 151 plots were sampled. An average of three plots of 100 m by 150 m were randomly selected within woodlands and burnt crop fields (very common in communities) and sometimes purposive sampling (for unburnt fields in some communities) based on information from farmers and community informants. Community members who were willing, allowed their farms and fallow fields for sampling. The farmers were selected from this group at random and their plots sampled. For woodlands, plots were selected using Standardised Random Table. Plot sizes were determined based on the average household farm size which range from one to two hectares (Bonye 2013). After demarcating the larger plots (10 m away from the edges of the sites) the centre of plot was determined as one subplot (20 m by 20 m) and other subplots demarcated at the four corners of the larger plots. Soils samples were collected at the depth of 0 - 5 cm (Pivello et al. 2010) using soil auger. Samples were collected from the four corners and the centre of each subplot and bulked together in clean polythene bags to form a composite sample per each subplot and five composite sample per a large plot (Figure 2). Geographical Positioning System was used to record the coordinates of the communities and the fields. Soils were sampled from 3 March to 27 April 2017, during the late dry-season.

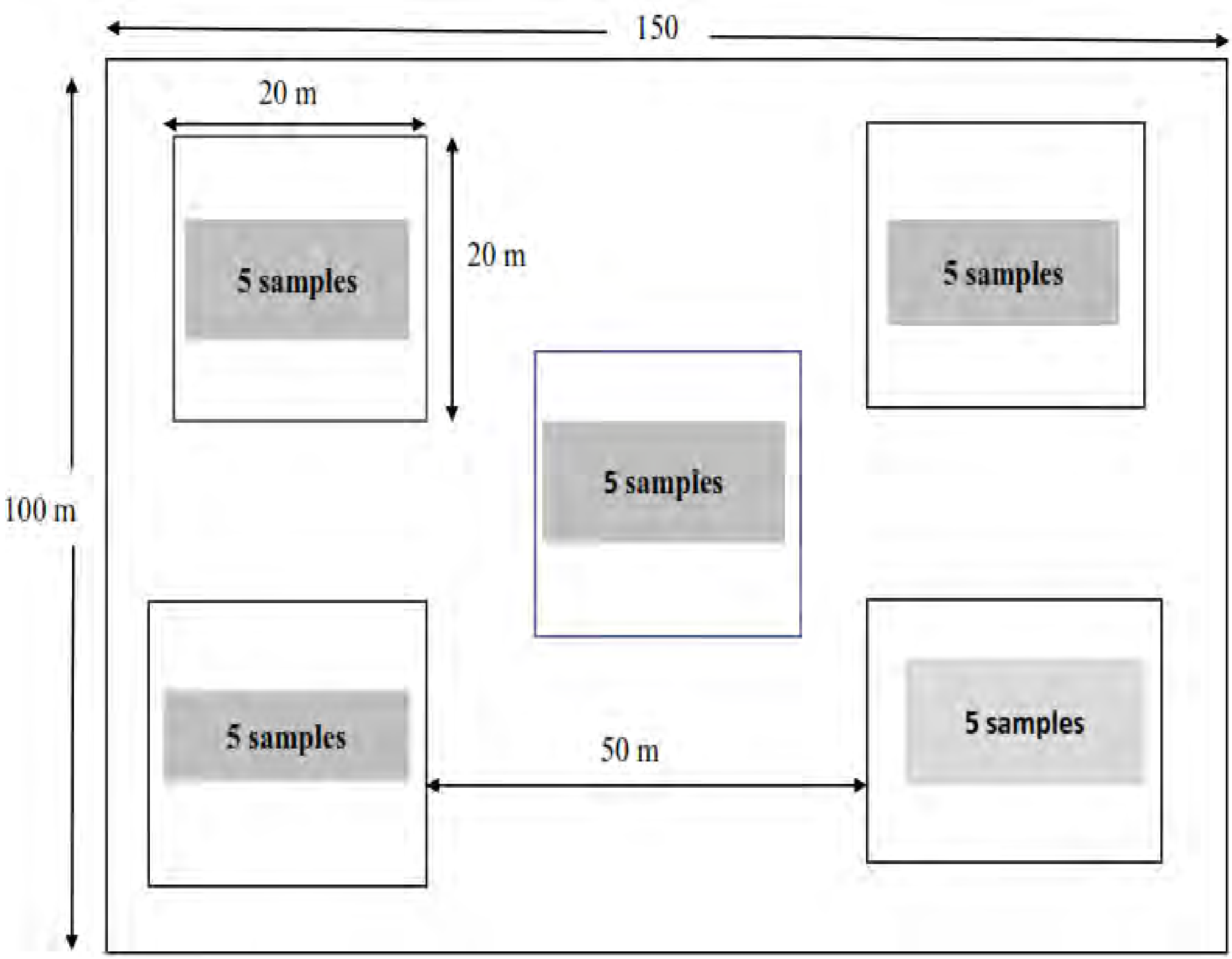


Figure 2. Sampling of subplots in a land use

Sampling

The 151 composite samples from the 10 communities were analysed for pH, organic carbon (OC), Total nitrogen (TN), Available phosphorous (P), Exchangeable bases - potassium (K), magnesium (Mg), calcium (Ca), cation exchange capacity (CEC), electrical conductivity (EC) and soil texture (sand, silt and clay) at the Ecological Laboratory (Ecolab), University of Ghana. Samples were air-dried, crushed and sieved through a 2 mm mesh. Soil pH was determined in a soil suspension of

1:2 and 0.01M CaCl2 using a pH meter (Kalra and Maynard, 1991). Soil organic carbon (SOC) was determined by wet oxidation – a modified Walkley-Black method (Walkley and Black, 1934). Total N determination was based on the macro Kjeldahl method (Bremer 1960). Exchangeable bases (Ca, Mg and K) were determined in 1N NH4 OAc extract of soil. Calcium and Mg were determined by atomic absorption spectrometry (AAS) and K by flame photometry (Moss, 1961). Available P was determined by the Bray 1 method (Bray and Kurtz, 1945) using 1 g air dry soil in an extraction solution of 15 ml of 1M NH4F and 25 l of 0.5M HCl and 460 ml distilled water. Electrical conductivity was determined by a conductivity meter and cell method (Piper, 1942; Rayment and Lyons, 2012). Soil texture was determined by the sieve and hydrometer method (Wen et al., 2002).

Data analysis

Data on soil nutrients from the four land use types and fire count data were checked for normality using the Shapiro Wilk test. Mean fire counts and fire densities were calculated for each district. One-way analysis of variance (ANOVA) was used to test for the significant differences in the fire counts data for the periods between January 2013 and December 2017. Data on soil properties were tested with Welch's ANOVA (McDonald, 2014) for statistical significances among the four land use types. Welch's ANOVA allows for heterogeneity of variances. Tukey's Honestly Significant Difference (HSD) was used to compare the differences in means among the land use types. Results were reported as statistically significant at $\alpha = 0.05$. A principal component analysis (PCA) and cluster analysis were also used to analyse the soil data to observe the trends, jump and outliers in the data as well as elucidate the relationships between and among observations and variables. The data analyses were done using R version 3.4.2 and RcmdrPlugin FactoMineR (Fox and Bouchet-Valat 2018).

Results

Fire frequencies of study districts

There were significant differences ($F_{5, 80.5} = 7.4$, $p < 0.001$) in monthly fire counts (i.e., from November to March) across the study districts over a period of five years (2013 to 2017). The highest mean monthly fire count for East Gonja (256.4±608.2) was 33 times higher than the counts in Tamale (7.83±19.2) which recorded the lowest fire counts (Table 2). Monthly fire counts in Tamale were significantly lower than counts in East Gonja ($p < 0.001$), West Gonja ($p < 0.01$), and Mion ($p = 0.01$) (Table 2). Fire counts in Tamale were significantly lower than counts in East Gonja ($p < 0.001$), West Gonja ($p < 0.01$), and Mion ($p = 0.01$) (Table 2).

Table 2. Fire counts from 2013 – 2017 (November to April).Values (mean ± standard deviation) labelled with the same letter in a column were not significantly different at $p < 0.05$ Source: AFIS/CSIR Meraka Institute, South Africa.

District	Fire count per 5 months		
	Mean ±SD	Minimum	Maximum
Tamale	22.2 ± 27^{a}	0	99
Tolon-Kumbungu	111.9 ± 118.7^{b}	2	469
West Gonja	610.2 ± 852.8^{c}	23	2910
West Mamprusi	206.2 ± 214.6^{ab}	6	641
Mion	253.24 ± 239^{ab}	14	826
East Gonja	596.2 ± 756^{c}	99	2472

Effect of fire on soil properties

Total N, OC, exchangeable Ca and pH showed significant differences among burnt or unburnt land use types (Table 3). Soil pH varied among the land uses ($F_{3, 70} = 4.4$, $p = 0.01$). Soil pH in burnt woodlands was significantly higher ($p = 0.04$) than that found in unburnt crop fields ($p = 0.05$).

There were significant differences in SOC levels across the land uses ($F_{3, 63} = 13.8$, $p < 0.001$). Percentage SOC in burnt woodlands ($p < 0.001$) was significantly higher than unburnt crop fields, unburnt woodlands crop fields ($p = 0.01$), burnt crop fields ($p = 0.02$). SOC was 1.2 times higher in burnt land use types than in unburnt land use types (Table 3).

Total N was also significant among the land use types ($F_{3, 65} = 20.04$, $p < 0.001$). The levels of TN in burnt woodlands and burnt crop fields were 1.14 times ($p < 0.001$) than that found in unburnt woodland and crop fields.

Similarly, exchangeable Ca levels showed significant differences among land uses ($F_{3, 65} = 3.3$, $p = 0.04$). The exchangeable Ca in burnt and unburnt crop fields were significantly lower ($p < 0.05$) than what was found in burnt woodlands ($p < 0.04$). The mean exchangeable Ca was 1.04 times higher in burnt than unburnt land use types, and 1.22 times higher in woodlands than in crop fields.

There were no significant differences in available P ($F_{3, 58} = 1.7$, $p = 0.17$), exchangeable Mg ($F_{3, 59.8} = 0.8$, $p = 0.5$), exchangeable K ($F_{3, 58.2} = 0.6$, $p = 0.64$), EC ($F_{3, 60} = 1.03$, $p = 0.38$), CEC ($F_{3, 63.6} = 0.86$, $p = 0.46$) among the land use types.

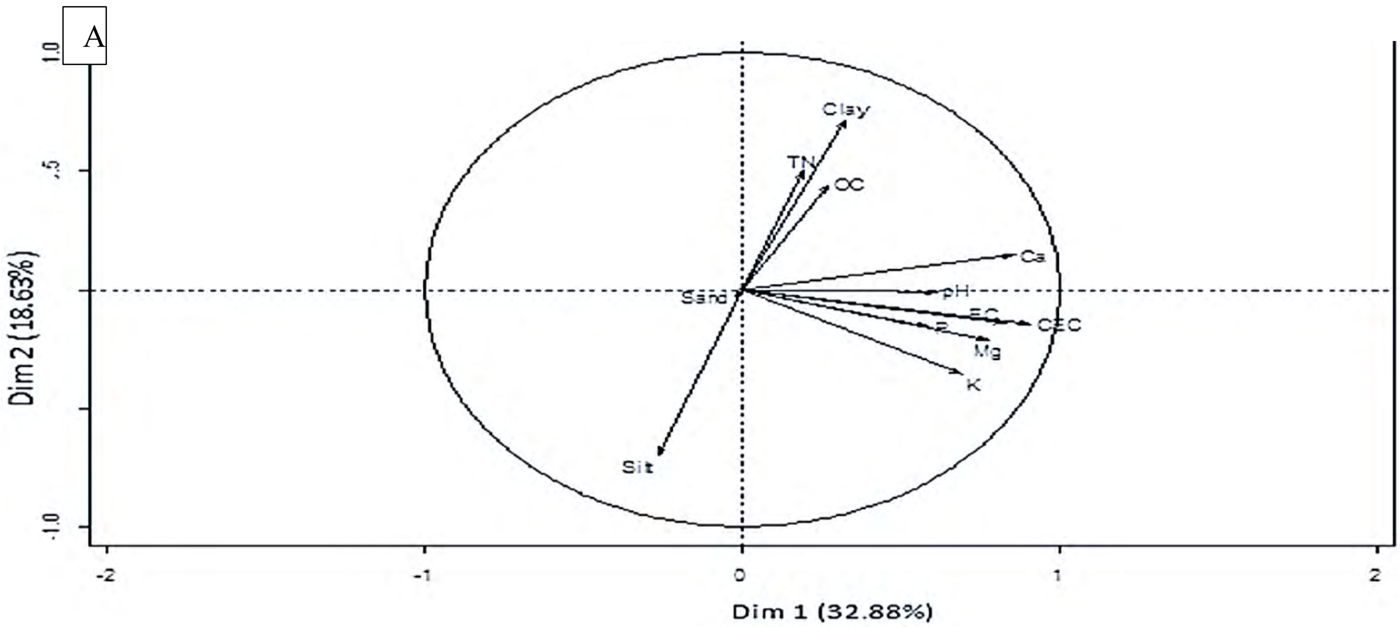
For the textural properties, there were significant differences in the relatively low clay content of soils across the four land use types ($F_{3, 64} = 4.9$, $p = 0.004$). The burnt crop fields had significantly higher clay content than that found in unburnt crop fields ($p = 0.02$), unburnt woodlands and burnt crop fields ($p = 0.03$). Silt content also differed significantly ($F_{3, 58} = 1.34$, $p = 0.04$) across the land uses, however, burnt crop fields was significantly lower than unburnt woodlands ($p = 0.03$), and burnt woodland ($p = 0.05$). Howeverthere were no significant differences in the sand content across the different land use types ($F_{3, 65.1} = 0.49$, $p = 0.68$) (Table 3).

Table 3. Mean (±SD) of soil properties in burnt and unburnt crop fields and woodlands

Soil variable	Crop fields		Woodlands		p Value
	Unburnt (n=4)	Burnt (n=6)	Unburnt (n=10)	Burnt (n=10)	
pH	6.5± 0.7[a]	6.8±0.3[b]	6.7±0.6[b]	7.0±0.6[c]	$F_{3,70}$ =4, p=0.01
SOC (%)	1.3±0.3[a]	1.6±0.5[b]	1.6±0.6[b]	1.9±0.5[c]	$F_{3,63}$=13, p< 0.001
Avail. P (mg kg^{-1})	14.6±8.5[a]	16.1±6.8[a]	17.3±6.7[a]	17.1±8.1a	$F_{3,155}$=2, p = 0.14
TN (%)	0.07±0.01[a]	0.08±0.01[b]	0.07±0.01[a]	0.08±0.01[b]	$F_{3,65}$=20, p < 0.001
K (cmol kg^{-1})	0.7±0.5[a]	0.6±0.7[a]	0.6±0.5[a]	0.7±0.6[a]	$F_{3, 58}$= 0.6, p = 0.64)
Ca (cmol kg^{-1})	3.7±1.5[a]	3.7±0.9[a]	4.1±1.4[b]	4.5±1.4[b]	$F_{3, 65}$ = 3, p = 0.04
Mg (cmol kg^{-1})	3.0±2.0[a]	3.0±0.9[a]	3.12±1.1[a]	3.3±1.7[a]	$F_{3, 60}$ = 0.8, p = 0.5
CEC (cmol kg^{-1})	9.0±3.6[a]	8.8±1.7[a]	9.1±2.2[a]	4.9±1.6[a]	$F_{3, 63}$= 0.7, p = 0.46
EC µs/CM	172.6±137.8[a]	146.0±74.3[a]	190.6±119.6[a]	174.0±107.3[a]	$F_{3, 60}$ = 1, p = 0.38
Sand (%)	42.0±7.6[a]	47.6±13.5[c]	40.6±12.5[a]	40.4±9.6[a]	$F_{3,65}$ = 0.5, p = 0.68
Silt (%)	43.8±16.4[b]	28.9±13.9[a]	44.6±12.6[b]	44.3±12.34[b]	$F_{3,58}$ = 1, p = 0.04
Clay (%)	14.2±15.0[a]	22.6±14.3[c]	14.9±14.3[a]	15.2±13.0[b]	$F_{3,64}$ = 5, p = 0.004.

For a given variable, values labelled with the same letter in a row were not significantly different at p < 0.05 (Tukey's HSD).

The output of the Principal Component Analysis (PCA) of soil nutrient variables accounted for more than 51 percent of the variance (Figure 3). Axis1 and Axis 2 accounted for 32.9 percent and 18.6 percent, respectively, which showed a positive association and an increasing gradient between TN and SOC (0.7), and available P and exchangeable Ca (0.5) in woodlands. Soil pH and the exchangeable ions also showed a somewhat positive association in unburnt crop fields and unburnt woodland, whereas silt showed a negative association (-0.5) to sand, clay, TN and SOC. The individual samples in woodlands showed a much wider variability with burnt woodland showing a positive association in clay, SOC and TN.



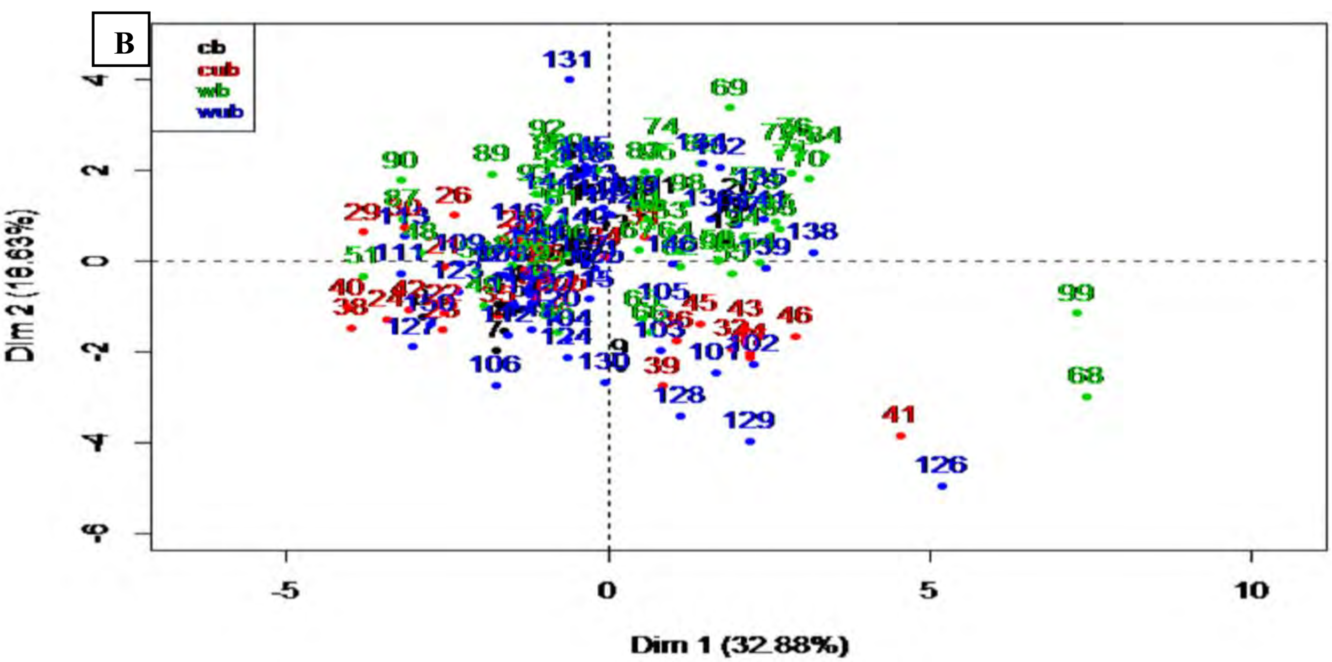


Figure 3A and 3B. Biplots of soil variables in the four land use types (cb, cub, wb and wub denote burnt crop fields, unburnt crop field, burnt wood land and unburnt woodland, respectively).

Discussion

Fire effects on soil properties

Generally, soils in the Guinea savanna of Ghana are sandy and low in nutrients (Bagamsah 2005; Tahiru et al. 2015). However, the levels of some nutrients found in this study were higher than what has been reported in other similar studies (Bagamsah 2005; Tahiru et al. 2015). The varying nutrient levels and textural properties in these studies may be attributed to the different depths at which soils were sampled, the time of burning within the dry season, the intensity of fire, the moisture content in soil, and the fuel load at the time of burning which was not known at sampling for this study. The significantly higher levels of pH, SOC, TN and exchangeable Ca content in burnt woodlands and crop fields show that fire chemically aided in the mineralisation of organic material in the topsoil (0-5 cm) (Owensby and Wyrill 1971; Sharrow and Wright, 1977; Mitros et al. 2002).

The mean pH between 6.5 and 6.9 found in this study is rather common to mineral soils in humid regions. However, the mean values of pH recorded across the land use types were higher than that reported by Bagamsah (2005) for pre-burning (5.3 ± 0.1) and post-burning (5.4±0.1). Again, this is probably due to the depth (0 - 5) at which soils were sampled in this study compared to 0 -10 cm in Bagamsah (2005). Because t soil pH also varied with depth (Bessah et al. 2016). The intensity of the fire and the time within the dry season at which samples were taken could also be a reason for the difference in pH in both studies. The peak burning time in the study area occurs between December and January (early dry season) and has been associated with low-intensity fires (Bagamsah 2005). This confirms Owensby and Wyrill's (1971) study that found that the charring of fuel during early spring burns resulted in higher pH of soils in Kansa rangelands than late spring burns. Further, Wardle et al. (1998) found that high pH in burnt debris aids in binding and releases phenolic compounds that enhance nutrient availability in soils. Knicker (2007) however, explained that increased pH after fire is the result of the liming effect which has a positive impact on the biological recovery of soil.

The levels of SOC found across the land use types were within the recommended levels of SOC (0.6% - 2%) in the Guinea savanna woodland (FAO 2005). The level of SOC found in burnt woodlands is about three times higher than the levels (0.6+0.02%) recorded after fire by Bagamsah (2005) which was rather a reduction in the levels (0.58 ± 0.03%) before burning. Rau et al (2008), however, reported an increase in SOC at the surface soils of burnt woodlands. Stromgaard (1992) also reported an increase in SOC content in the top soil (0 - 10 cm) of the Zambian Miombo woodland after fires. Comparatively, the higher SOC levels in burnt land uses than unburnt land use ones, may also be due to charring from incomplete combustion of organic material (Kauffman et al, 2018). Conversely, Certini (2005) argued that fire-induced increase in SOC could be due to the decline in mineralisation rate of organic matter as a result of a decrease in microbial activity immediately after fires. Nonetheless, in contrast to what was observed in this study, Chan and Heenan (2005) found that unburnt crop fields had higher SOC than burnt crop fields.

The levels of TN found in burnt plots indicate the rapid oxidation of N in burnt fields, which normally occurs a few days after fire as shown in similar studies in Central Brazil (Nardoto and Bustamante 2003; Pivello 2011). However, the studies indicated a decline in N levels within a month after the fire, when compared to pre-burnt levels in close up (Nardoto and Bustamante 2003; Duguy et al. 2007; Pivello 2011). In contrast, Mitros et al. (2002), found no significance difference in TN between burnt and unburnt plots in the CERA oak woodlands, California. Thus, for long term maintenance of TN in soil, other factors such as rainfall, sustainable land use practices and biological fixation, other than burning, can influence the levels of TN in soils.

The association between TN and SOC in the PCA implies that an increase in TN will correspond positively to SOC and vice versa (Schrumpf et al. 2014). The strong positive association within individual samples in burnt woodland implies that, to a large extent, fire had a positive influence on soils in woodlands – probably through the release of nitrogen that has been tied up in growing and dead plants. This could also be due to the peak period of burning being in the early dry season, so that burning did not have a devastating effect on SOC and TN (Pivello et al. 2010). Similar studies (e.g. Sharrow and Wright, 1977; Raison 1979; Stromgaard 1992; Pivello et al. 2010) have reported an increase in soil nutrient content and availability after low-intensity fires. But these studies also indicated that the levels declined with time, particularly for TN (Sharrow and Wright, 1977).

The results in this and other studies, suggest that burning enhances short term availability of some soil nutrients in top soils (e.g., Raison 1979; Stromgaard 1992; Pivello et al. 2010. This suggests that burning for nutrients as practised by most subsistence farmers may not be a sustainable way of increasing soil productivity. Nitrogen can be volatised at a low threshold of 200^{o}C (Chan and

Heenan, 2005). Thus, the dynamics of the effect of fire and fire regimes in the savannas need further research because Bagamsah (2005) indicated higher nutrient loss in the early dry season than late season fires in the study area. Some studies have however indicated enhanced soil nutrient after early burning (Pivello et al. 2010).

The relatively high content of silt found across the land use types is attributed to the depth (0-5 cm) at which samples were taken and the season of sampling: the dry season in the Guinea savanna of Ghana is characterised by a high deposition of silt from the North Easterly winds (Harmattan) from the Sahara Desert (Bagamsah 2005). The significantly low content of clay found in the land use types can negatively affect the colloidal levels in the soils hence the soil structure (Braimoh and Vlek 2008; Bessah et al. 2016). Similar studies on the effects of fire on soils have found more sand in burnt fields than unburnt fields (Ulery and Graham 1993; Bird et al. 1999; DeBano 2005). Thus, continuous indiscriminate burning in a high sand content soils as found in most part of the Guinea savanna could change soil structure in the long term (DeBano 2005).

The implications of fire frequency in the study districts

This study confirmed seasonal fire recurrence in the Guinea savanna (November to April) (Korem 1985; Andersson et al. 2003; Bagamsah 2005; Sackey and Hale 2008; Kugbe et al. 2014). Previous studies on fire in the study area (Korem 1985; Bagamsah 2005; Sackey and Hale 2008) and observations made during the fieldwork are evidence of burning by most of the study communities. Data on fire in the savannas of Ghana is, however, limited to frequency and season. The discussion on fire frequency in this study is therefore, based on the occurrence and counts of fire in the dry season (Table 2). Available records for five a year period showed a range of 6,213-1,5254 counts in high fire frequency, 2,804-6,213 counts in moderate fire frequency and low fire frequency 487-2,804 districts. Knowledge of frequency and season of fire use are available in the study communities. However, there was no record on the intensity and the type of fire on all plots sampled. Thus, the plots did not have the same fire regime since burning was done at different times of the year and at the farmers' discretion.

The districts that recorded high mean fire counts (Table 2) are large areas of open savanna woodland and wet savannas with high game populations and tall grass growth (*Andropogon* and *Hyparrhenia* spp) (Andersson et al. 2003; Bagamsah 2005; Bassett et al 2003; Kugbe 2014). A good rainy season promotes high growth of grass and coupled with the Harmattan conditions, can drive extensive fires. The high fire use in this area may be attributed to hunting (to flush out rodents and small animals and attract animals for hunting) as well as for farming and charcoal burning (Korem 1985; Day et al. 2014,). The West Gonja – for instance, is characterised by high game populations and contains the Mole National Park (4,840 km^2). Most people in this area engage in hunting and charcoal burning, either as their main or an alternative livelihood activity during the dry season which involves the use of fire (Adongo et al. 2012). The provision of alternative livelihood income sources to these communities and the responsible use of fire could curb the indiscriminate use of fire (Bonye 2013).

The fire low count districts are relatively dry with low rainfall constraining grass growth (Andersson et al. 2003). Moreover, some communities such as Nwodua (Table 1), in the low fire density districts are known to have practised no-burning for more than 20 years (Andersson et al. 2003). An observation made during sampling was that, communities such as Nwodua and Katabanawa, have relatively small areas of arable land, hence the intensification of crop farming in these communities (Rhodes 1999; Kotu et al. 2017). Thus, the farmers in these areas indicated that they found no-burning as a way of improving soil productivity as observed by Chan and Heenan (2005). Interactions with farmers revealed that they do not burn the crop residue but rather plough the residue into the soil. In addition, some of farmers supplement soil nutrients by applying inorganic fertilisers to maximise crop yield per unit area to continuously use the same piece of land.

Jagriguyilli community, on the other hand, is known for the preservation of one the largest sacred groves in the north of Ghana, the Jaagbo sacred grove (1 km^2). The grove is believed to house a twin god which protects the surrounding communities from diseases, thus the area is protected against fire through the creation of fire belts around the grove to ensure a peaceful abode for the gods (Oteng-yeboah 1996; Telly 2006; Omsby 2012). This was also observed in the Tugu community where there was evidence of fire very close to the sacred grove but not in the grove because the gods must be protected against fire. Again, large unburnt areas were identified in Jagriguyilli and Nwodua, in the Tolon-Kumbungu district. These two communities have been internationally recognised, with Jagriguyilli having been awarded a UNESCO heritage status since 1993 (Oteng-yeboah 1996; Telly 2006; Poreku 2014). These traditional practices could be a model for other communities within the study region. This can be achieved through community mobilisation and sensitisation. The lowest mean fire count recorded in the Tamale area is however, attributed to the large human population with a relatively small land area, the expansion of the built environment and a decrease in the natural environment.

Conclusion

This study confirms that vegetation burning is recurrent in the dry season in Guinea savanna ecological zone of Ghana – with East Gonja district recording the highest density amongst the study districts.

The results showed varying influence of fire on both the chemical and physical properties of the soils across burnt and unburnt woodlands and crop fields. There was a seemingly positive but probably short-lived influence of fire on pH, TN, SOC and exchangeable Ca in the soils. Soil pH, TN and SOC and were at optimum levels, according to the savanna recommended levels for crop production, and the results revealed a positive association between clay, TN and SOC. The proportions of sand and silt found in each land use were nearly homogeneous in content with very low clay content. The relatively high TN and SOC contents in burnt crop fields and burnt woodlands confirm why farmers would burn: to increase soil nutrients for crop production.

Nevertheless, rural communities that use fire for livelihood activities can be sensitized on the long-term implications (e.g., loss of volatile nutrients and living organisms) of indiscriminate burning on soils and the environment as a whole. Cultural and traditional belief systems on burning and non-burning could also be harnessed to reduce the indiscriminate bush burning.

The conclusions drawn from this study are based on the number of fires and the seasonality of fire in the Northern Region. The intensity, size and pattern (types of fire), are still understudied in the Guinea savanna. These factors are, however, crucial in determining the wholistic effects of fire on soils in the savannas of Ghana, and require further investigation.

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CHAPTER SIX: GENERAL CONCLUSION

Introduction

Savannas are characterised by the presence of fire which can be traced back to around 10 million years ago (Staver et al. 2011; Knowles et al. 2016; Osborne 2018). For instance, up to 50% or more of the savanna landscapes of northern Australia and sub-Saharan Africa are burnt each year (Orgeas and Andersen 2001; Ramo et al. 2021). Several studies (e.g., Staver et al. 2011; Dwomoh and Wimberly 2017; Nyongesa and Vacik 2018) have shown that the use of fires for cultural and socio-economic activities are associated with hunter-gatherer and pastoralist lifestyles as well as for crop farming. Thus, approximately 90% of fires in Africa are caused by humans (Knowles et al. 2016; Dwomoh and Kimberly 2017). The use of fire is therefore overwhelmingly rooted in rural Africa, where about 65% of the population of sub-Saharan Africa live (OECD/FAO 2016).

Nevertheless, African savannas have a high use-value due to their high species diversity endemism and continue to provide ecosystem services including food, clothing, medicine, energy and shelter to the inhabitants (Chidumayo 2010, 2013; Treurnicht et al. 2013). Some studies have indicated the beneficial role of the effects of fire on savanna species abundance, richness and diversity (pyrodiversity) (Parr and Andersen 2009; Andersen et al. 2014; Bowman et al. 2016). The effects of fire are also of great importance to soil nutrients and texture (Stromgaard 1992; Zhao et al. 2012). Thus, fires have many implications for biodiversity at the local and global scale over time (Orgeas and Andersen 2001; Keith et al. 2014). At the regional and local level, they may lead to changes in biomass stocks and species diversity (OECD/FAO 2016).

However, there are reported incidences of degraded landscapes and species loss, due to the over-manipulation of fire to achieve livelihood benefits such as hunting, clearing areas for farming and fire for tapping honey for household and commercial purposes (Chidumayo 2013; Trauernicht et al. 2013; Ricketts and Shackleton 2020). At the global scale, it is acknowledged that biomass losses occur over periods of hours to weeks, depending on the occurrence of fire (Davies and Unam 1999; Gill et al. 2009; Keith et al. 2014). Davies and Unam (1999) reported that smoke from fires can reduce photosynthesis of some plant species. In fire prone savannas, annual fires may affect the seed bank, seedlings and saplings negatively which hinders recovery of some indigenous species (Lulu and Gambiza 2007). The degree of recovery and need for rehabilitation interventions depends on the intensity of burning (Orgeas and Andersen 2001).

The intricacies of fire impacts on the environment may be ascertained by a framework that is all encompassing - that considers how humans have interacted and influenced the environment particularly vegetation and soil through the use of fire. Thus, as reviewed in Chapter 1 of this thesis the social-ecological framework as an integrated approach was used to ascertain how anthropogenic fire uses have influenced the woody species and soils in the Guinea savanna woodlands and parklands. Although, Stojanovic et al. (2016) mentioned some weaknesses in capturing certain social realities such as individual motives and action using the framework, this study successfully weighed people's perception about a fire regime, the frequency, season of fire use as well as control practices. Synthesising the factors that influence people's perceptions, knowledge, and fire use is integral to future research, to facilitate dialogue and negotiation between actors, and to aid management and policy formulation and governance of savannas in Ghana and West Africa as whole.

In the agroforestry parklands of West Africa, woody species (usually preferred species or trees with economic value) are sparsely distributed on farmlands through careful selection of these species and also through the use of fire (Blench 2001). *Vitellaria paradoxa* and other fire-resistant species of the Combretaceae are commonly found in the parklands. Fire is used to clear the land of grass and stubble before and after cropping, respectively. This practice of burning in the Guinea savanna is quite different from the slash and burn agriculture practised in the south of Ghana and other parts of Africa (e.g., Chitemeni in Zambia). In this practice of land clearing in the Guinea savanna, the whole area to be cropped is burnt to get rid of unwanted grass and other herbaceous plants.

As mentioned in the introduction of this thesis, Laris (2011) and Huffman (2013) have described this type of burning as open native vegetation burning. The authors acknowledge that this form of burning consumes dead and dry grasses, tree litter, shrubs, seedlings and saplings. The reasons for fire use are for many different purposes and the impact vary depending on the fire regime and prevailing environmental factors. The challenge is that, apart from season and frequency of fire, other attributes of a fire regime are rarely considered important by local people as revealed in this study (Chapter 2). Attributes such as intensity or temperature, flame height, residence time, in uncontrolled burning are rarely considered in traditional fire use (Huffman 2013).

However, the effects of fire in parklands are as a result of all these composite attributes, but the practical details of the different methods from place to place are lacking. Thus, it is difficult to tell which methods enhance or deplete savanna species. For instance, some research conducted in the Guinea savanna of Ghana, indicated a gradual transformation of the Guinea (wooded) savanna into a Sudan (sparsely populated woody species with more grass growth) savanna, as a result of the intensification of agriculture accompanied by the extremely frequent use of fire (Blench 2001; Bagamsah 2005). Bilbao et al. (2009) also stated that fires in the Canaima National Park, Venezuela, affected the wooded areas, transforming them into treeless savannas. In contrast, fire was found to have positively affected seedling emergence, flowering and survival of some woody species in Brazil and West Africa (Gignoux et al. 2009; Cardoso et al. 2009, 2016).

The review on soils in Chapter 1 of this thesis, highlighted that soil properties are fundamental to the sustainability of savannas and all vegetation types. Thus, many authors (e.g., Basett et al. 2003; Vogt 2015; Santin and Doerr 2016) have indicated the direct and indirect impacts of fire on numerous mechanisms that affect soil nutrient pools and cycling. Certainly, soil-fire relationship is important in the determination of the type of vegetation in an area. However, the other studies have indicated a negative effect on seed bank at a temperature of 200ºC (Santin Doerr 2016). Fires are also important in the mineralisation of some soil nutrients including nitrogen as found in this study and other studie (Bagamsah 2005; Kugbe et al. 2012, 2014). Lead on the other hand, can easily volatise within the same temperature (Santin Doerr 2016).

Indeed, there is a broad knowledge base of fires in savanna leading to the generalisation of fire effects on environment, however, fire effects vary across spatial and temporal scales, thus the need for some specificities in terms of the local and regional impacts of fire that can enhance local content solutions and policies to curb the indiscriminate use of fire and promote appropriate fire management, hence, the aim of the research in the Guineas savanna of Ghana.

Discussions and synthesis

As postulated in this research, three tiers of the social-ecological framework were adapted to answers to people's use of fire and effects of fire on the environment. The Resource systems (Tier 1) which is presented as the Guinea savanna parkland and the Resource units (Tier 2) representing the vegetation and soils variables which were analysed quantitively. People's perceptions (Tier 3) of the use of fire were also investigated. Thus, fire use by people and its influence on the Resources system through assessment of feedback from the Resource unit was achieve through the application of standard scientific methods of data collection, data analyses to produce the results, discussion and conclusions in each of the four chapters (2, 3, 4 and5). The original intention of assessing the Governance Tier, which I believe affects the Governance of the parkland systems (Tier 4) could not be met due to time and financial constraints.

There were a few challenges in the questionnaire administered to answer Question 1 of the study, which include the translation and interpretation of questionnaires into the three major ethnic dialects. This was however, overcome by recruiting research assistants who are natives of the six districts. Apart from the data collection at the Mole National Park, there was also a challenge of tree species identification and sorting of specific species (*A. leiocarpa* and *V. paradoxa*) among the lot that were identified in the plots.

A strength of this study is that respondents and farmers who were randomly sampled for questionnaire administration, species and soil sampling, had good knowledge of the frequency, reason and season of fire use. However, there were no records of fire attributes such as the intensity and the type of fire on all plots sampled. Thus, the plots did not have the same fire regime since burning was done at different times of the year and at the farmers' discretion. Thus, the analysis of results was based on frequency and season of burn.

Knowledge, perceptions and practices of fire use and fire regime

The use of fire is recognised globally as an influential land use tool with extensive impacts on savannas (Furley 2010; Knowles et al. 2016). However, the observation made in this study was that fire use is usually livelihood-driven rather than a direct management tool for vegetation as practised in conventional protected areas. Other studies on fire use in East Africa (Kikula 1986; Nyongesa and Vacik 2018), Southern Africa (Kapekele 2006; Archibald 2016) and Australia (William 2000) have also indicated the causes and use of fire as livelihood-driven. Thus, the use of fire is embedded in the cultural practices of most rural dwellers in savannas around the world.

As mentioned earlier in Chapter two of the thesis the government of Ghana promulgated the 1983 anti-bushfire law (PNDC Law 46) to prohibit the setting of fires except for certain agricultural, forestry or game management purposes. This law was intended to protect land cover, wildlife and habitats. However, the oversimplification of the relations between human beings and natural resources and the one-size-fits-all recommendations made by managers and regulators have produced mismanagement and failures.

Nonetheless, taking a holistic approach of reviewing factors that influence the perception, knowledge of anthropogenic fires will be beneficial for future research, management, policy formulation and governance. The reason for the adoption of the Ostrom's (2007) social ecological framework that recognises human (actors) and their interaction with natural resources as integral in the management of natural resources. The integrated approach adopted by this study which considered the knowledge and perceptions of fire use in agroforestry parklands and woodlands systems can inform and improve broader stakeholder engagement towards sustainable savanna parkland and woodland management considering different knowledge systems.

This present study confirms the causes of fire in the Guinea savanna of Ghana, where over 80% of the respondents use fire for land preparation for cropping, as revealed in the questionnaire survey (Research Question 1). Similar studies in the forest zone of Ghana and Kenya also revealed that the highest number of people use fire once a year for land preparation (e.g., Appiah et al. 2009; Nyongesa and Vacik 2018). In West Africa, fires are usually difficult to control during the Harmattan -North-Easterly wind characterised by very low humidity and relatively high windy conditions occurring between November and April. This shows fire as a livelihood tool in most rural communities may come with unintended consequences. Thus, fire use could be beneficial or destructive to plant communities and soils depending on a wide range of factors as discussed in the introductions of Chapters 1, 3, 4 and 5.

As revealed in the study (Chapter 2), the majority (77%) of the respondents (were of the view that fire is not good for the environment but then, greater majority (83%) also use fire for the selected activities in Chapter 2. I see this as a"dilemma" of fire use in this region. Well, I asked the question after analysing the data; if fire is not good for the environment, why the high number of people using fire? I find in this study, that the use of fire is livelihood-driven and a cultural practice. Also, people are not aware of the benefits of fire to savannas as a whole and as mentioned earlier in Chapter 3, people hold unto the colonial restrictions of fire as bad for the environment. Thus, the use fire is perceived as negative by many people including those who use fire. These findings are supported by Laris and Wardell (2006) emphasising the need for reinterpretation of colonial fire experiments in Africa. Huffman (2013) on the other hand mentioned that, the younger generation is gradually losing the essence of traditional fire use.

The regression analysis in Chapter 2 revealed that occupation, ethnicity, age, district and gender are predictors of fire use, the season and activities that fire is used for. Indeed, fire is mostly used for land preparation for cropping rather than charcoal burning. The study revealed that the Dagomba ethnic group used fire more often than the other ethnic groups like Mamprusi, which is another major group in the study area. Similar to other cultural practices such as fire stick farming of the Masai of Kenya, the Aborigines of Australia, the Māori of New Zealand and native Americans (Baillie and Bayne 2000; William 2000), fire practices are embedded in the culture of the people of the Northern region, Ghana. Indeed, there is a fire festival celebrated annually, which is linked to the spirituality of the people. It not surprising that more respondents in the age group of 25–51 years who were farmers, use fire for farming (crop production).

Nevertheless, some studies (Shaffer et al 2010; Nyongesa and Vacik 2018) have indicated that fires set deliberately are always controlled, to achieve the desired purpose and reduce damage to the natural resources on which they depend, as well as to ensure a continuous supply of the benefits derived from the savanna (Chidumayo and Gumbo 2010). This present study confirms this practice of fire control, particularly in crop fields during land preparation (Chapter 2) but also in community-protected woodlands, including sacred groves (Research Question 2 Chapter 4). Respondents of the survey indicated that they control fire through the creation of fire belts and burning early in the fire season (Chapter 2). Thus, rural people's awareness of hazards of uncontrolled burning could be harnessed to promote good fire practices and management. This knowledge could be a start-up to identify the ecological effects of traditional fire use through the integration of historical and current human fire use ecology to inform fire policies at the district, regional and national levels (Mistry et al. 2016).

On the concept of fire regime, respondents perceived the season of burn as the most important (Chapter 2). This suggests that the season of burn determines the frequency of the fires, as the dry season spans six months in the Guinea savanna, the highest percentage of respondents indicated they burnt once per year (Chapter 2) – thus fire use has an annual return interval (annual cycle) in the region. There are discussions (Laris 2016, 2020) on whether the time of burning within the fire season (early, mid and late) have varying impacts on the vegetation differently. However, this study confirms only two burning times as observed in the burning treatment at the Mole national Park. At the community level, there may be a mid-season but the local people do not recognise that. The general perception is that burning is done when vegetation is not too dry (early season) or when it is dry (late season). The complexity of whether it is early, mid or late fire on depends on the time the rain ends and the farmers discretion (Huffman 2013). The fire data report from the CSIR Meraka Institute and AFIS show a trend of fire use in the West Africa savanna with peak burning periods in January (Laris and Wardell 2006).

Unlike fire management at government conservation sites and protected areas as observed in the Mole National Park (Chapter 3), in rural communities it is a challenge to regulate the type of fire, intensity, severity, fire behaviour as well as other minor fire attributes such as heat output, residence time and flame height (Huffman 2013). Bagamsah (2005) and Kugbe et al. (2012) explained that the season of burn occurs during the Harmattan period, which is characterised by very low humidity (9% by the end of the season), windy and hazy conditions which can result in high-intensity fires. For instance, Kugbe et al. (2014) was able to monitor controlled burn of duration 17 minutes with a maximum wind speed of 2 km per second and a temperature of 899^{o}C in January.

However, the respondents' perspective of these attributes as not very important can be understood because it is difficult to measure these attributes such as intensity during traditional burning. In contrast, responses from the local communities are that it is very easy to determine the time to burn in the dry season and how many burns would need to complete an activity like land preparation. Again, the respondents mentioned that burning is usually done when the vegetation is not too dry - at the beginning of the dry season (Chapter 2). But the timing also depends on the farmer's discretion of what is not too dry and what is dry. Thus, rural people who use fire depend on their indigenous ecological knowledge as reported by Huffman (2013), which may however, lack precision; hence fires may become devastating rather than beneficial.

Some studies (e.g., Archibald 2010) reported that high fire frequency reduces the fuel load for other burns, and therefore results in low-intensity fires. The situation in the Guinea savanna on the other hand is that, it rains between 120 and 180 days (Obuobie and Barry 2005) during the rainy season with an average temperature of 27^{o}C. These are very good conditions for high grass growth and high fuel load, and thus fires may burn for a longer duration in early season burn than late-season (Kugbe et al. 2014). This explains N'Dri et al.'s (2018) finding that the late season fires did not damage woody species at Lamto Reserve Reserve, Ivory Coast, because trees lose their leaves to the Harmattan conditions before the late season fires.

As mentioned earlier, it is challenging to manage some aspects of fire regimes in rural areas. However, the conceptual framing of the social-ecological systems, indicates the linkages in the biophysical systems, social systems (e.g., actors) and institutions (formal and informal). Thus, some commonalities in traditional and cultural uses of fire, in addition to the knowledge of climatic conditions, can inform and enhance fire policies. Fire management policies should, therefore, delineate the different aspects of management especially community lands fire management and government/conservation fire management to enhance the adoption and implementation at all levels (local, regional and national).

The effects of fire on natural resources should be managed, with the integration of traditional and scientific knowledge, as this has shown success in some countries like Burkina Faso (Makela and Hermunen, 2007) and Indonesia (Carmenta et al. 2017). Ghana can learn from neighbouring country Burkina Faso where indiscriminate bushfires are prohibited, but management fires (controlled burning for agricultural purposes) and customary fires managed by a traditional authority and village land management committees are allowed (Makela and Hermunen 2007). For traditional fire usage traditional leaders are capable of regulating it usage. Thus, the need to apply the SES framework in agroforestry parklands of West Africa where land and tree tenure systems are mostly customary.

Land use, fire count, fire effects on vegetation and soils

As observed from question one, there are linkages between fire use and livelihood activities, thus an extended influence on soil and vegetation. Thus, answering questions (2, 3 and 4) on fire effects on woody species and soil properties were based on a five-year daily fire count data (2013 to 2017) for Ghana from the CSIR Meraka Institute, South Africa. Plant species were analysed using percentage frequencies, density and diversity indices, DCA and size class distributions in unprotected area and a protected area. Soil samples were also analysed using the standardised methods and protocols.

The study observed a reflection of the fire count data as the frequency of fire usein the Guinea savanna of Ghana that is characterised by land use and cultural practices. The low fire count recorded in Tamale is due to Tamale being the smallest of all the districts and having a comparatively much larger built-up environment and population than the other five districts, hence, less farming (Chapters 2, 4, 5). The high fire counts recorded in the West and East Gonja (characterised by vast woodland areas) are attributed to both farming and hunting. Nonetheless, this study and other researchers (e.g., Vigilante and Bowman 2004; Zhao et al. 2012; Múgica et al. 2018) have shown that for whatever purpose that fire is used (Chapter 2), there is an overtime effect on the environment, including woody species (Chapters 3 and 4) and soil properties (Chapter 5).

It is widely acknowledged that fire can either directly or together with other disturbances, have modifying effects, or can create new vegetation biomes (Hobbs et al. 2009). This is observation for *Vitellaria paradoxa* which predominantly increasing in high fire frequency districts as observed in this study. This study has also confirmed by showing the different structural parameters of the two economically valuable woody species (Chapter 3), the impact of fire in communal woodlands and parklands where people use fire for charcoal-making, hunting/poaching, honey harvesting, and in the parklands where cropping occurs. The results of the study reflect the practical and cultural use of fire, as well as the regulated use of fire in a government-protected area, where livelihood activities are prohibited. To give a general overview of the effects of fire in the woodlands, and agroforestry parklands of the Guinea savanna, it was necessary to compare effects of fire on two economically important woody species, soil properties in burnt and unburnt woodlands with burnt and unburnt crop fields, fallow fields and sacred groves and a protected area.

For the tree species population structure analyses, the size class distribution in the fire frequency zones depicted the survival and abundance of *A. leiocarpa* and *V. paradoxa* in low and high frequency districts, respectively. Again, the vulnerability of both species is also shown in the moderate fire frequency districts that displayed bell-shaped and nearly flat structures. Nonetheless, bell-shaped distributions have often been associated with long-lived plants such as the species under study (Cousins et al. 2014). This is probably prevalent in high disturbed environments so that regeneration is mostly interrupted or absent (Lykke 1998).

Specifically, the observed and Weibull representations of the population distribution of the two study species (*A. leiocarpa* and *V. paradoxa*) illustrate their survival in burnt woodlands, unburnt woodlands, burnt crop fields, unburnt crop fields, sacred groves and fallows in the communal fields. It is evident that *A. leiocarpa* as a pioneer species (Sanogo et al. 2015) cannot withstand disturbances from fire and cropping and therefore needs protection, as the study revealed the highest mean densities of adult and juveniles of *A. leiocarpa* in sacred groves, unburnt woodlands and unburnt crop fields (Chapter 3). The communal sacred groves and unburnt woodland are 'safe havens' for the two species, particularly *for A. leiocarpa* which recorded the highest juvenile density in unburnt woodlands. This was echoed again in the inverse-J shaped size-class distributions observed in sacred groves and the woodland which is an indication that the protection of species through no-burning would enhance regeneration, establishment and the recruitment. Again, the bell-shaped distribution and absence of regeneration observed of *Anogeissus leiocarpa* in crop fields and fallows can be attributed to disturbance from fire and cropping.

However, a few *Anogeissus leiocarpa* trees were recorded in some burnt woodlands in the communities and late burning plots in the Mole Park. This implies that either the late season fire is regulated well enough to prevent destruction to woody species or the species is probably adapting to the frequent fires in the Guinea savanna. This confirms observations by Govender et al. (2006), Lykke (2008) and Trollope (2011) on the adaption of species to fire conditions over time. The DCA scatter plot of species in the three burn treatments in Park showed that the time of burning has marked effects on woody species composition which was reflected in the species diversity and density amongst the treatments. The analysis showed a changing trend, indicating a moderately strong positive association between burning time and species. This study also confirmed the prevalence of species of the Combretaceae in the Guinea savanna which are generally fire resistant but can also survive under no-burn conditions. It was, however, observed that *Vitellaria*, a Sapotaceae is gradually becoming dominant in woodland and farmed parklands.

For soil properties, the relatively high levels of N, OC and Ca found in soils in burnt woodland have also been observed in other studies (Stromgaard 1992; Pivello 2011). Knowles et al. (2016) observed that the short-term increase in soil nutrients after fire is the reason why most farmers burn. Although other studies (Chan and Heenan 2005) observed a decline in these nutrients after some time, the practice of burning was found in this study to be annual and these nutrients are presumably made available after every burn because of the high fuel load after the rainy season. By burning, some nutrients are added to the soil so that chemical fertilisers, which are now very expensive even at a government-subsidized price of USD 25 per 50 kg, are added to the burnt fields in low quantities as a supplement. Farmers would normally leave the farmland as fallow after several years of cropping when the soil is depleted of nutrients. This presupposes those farmers have used this knowledge over time, know and understand why they burn.

Given the ever-changing savanna landscapes through large-scale burning, it would seem impractical and idealistic to suggest sustainable management for the whole of the Guinea savanna of Ghana when there is not enough research and knowledge on what the net changes through the cultural use of fire. There is a need for adaptive management of the Guinea savanna, which would require different management strategies at the landscape level, with the different stakeholders as proposed in the social-ecological framework discussed in Chapter 1 (McGinnis and Ostrom 2014).

Conclusion and insights for future research

The high fire count recorded in the study districts has some implications for the Guinea savanna resources management in this era of changing climates. Analysis of the fire count data revealed that January is the peak period for fire use in the Guinea savanna, with the West Gonja District recording the highest fire count. This study revealed that most burning is done early in the dry season. The results from the questionnaire survey confirmed that most of the fire is for agricultural purposes particularly clearing of land for crop preparation. There were number of people who use for fire but ironically, think that fire is not good for the environment but then need to use fire for livelihood purposes.

The study revealed that the two economically important species - *A. leiocarpa* and *V. paradoxa* are threatened in crop fields but are well preserved in woodlands and sacred groves. However, with the expansion of crop fields into woodlands in the study area, a continuous loss or decrease in woodlands through the livelihood activities and cultural practices could threaten the abundance and population structure of the species, especially *A. leiocarpa*. *Vitellaria paradoxa* seems to have some resilience to these fire conditions but will still need to be protected and conserved. Communities protect this species against other disturbances as it has a higher economic value than *Anogeissus leiocarpa* in the study area. The differences observed in the theoretical distributions of the species in the different land use types do not only illustrate each species' level of tolerance to fire but also to cropping. Although densities of *V. paradoxa* seems to thrive in both burnt and unburnt land uses, the reduction of juvenile *V. paradoxa* and the total absence of *A. leiocarpa* show that apart from pressure from fire, the increasing use of the plough for land preparation and other disturbances negatively affect the population of these species in the traditional agroforestry parklands of West Africa.

The seemingly positive fire impact on some major soil nutrients (OC, N, Ca) suggests that is the reason why farmers burn trash, dry grass and other herbaceous material: to add nutrients to the soils for the next cropping season (as revealed by some respondents). Concerning the increase in major nutrients found in the soils, the study confirmed a high use of fire for land preparation for cropping. This study also observed that the method of burning for land preparation is different from slash and burn as practised in the southern part of Ghana, where the herbaceous layer is slashed with a machete, the debris is allowed to dry, then gathered and set ablaze. This "savanna method", also described as open native vegetation burning where the plot of farmland is set alight, could have a greater repercussion on seedlings and saplings than the slash and burn methods. A comparative study on these two methods, as they pertain to Ghana, would be useful. Thus, this study would be a reference to future studies that would evaluate the fire effects in the Guinea savanna.

Collaborative management with communities to sustain community-protected areas is one aspect that requires further research. There has always been an attempt to consider community collaboration for the management of government-protected areas which have not been successful. For instance, the community resource management area (CREMA) project led by the Ministry of Natural Resources and Environment in collaboration with the UNDP, Ghana, which aims at empowering communities to manage natural resources sustainably has faced a lot of challenges than successes. However, there are a lot of successes in community-owned initiatives in the conservation of species which must be promoted.

Although it is well known that the fires in the African savanna are human-related or set by humans for livelihood activities, most studies on fire in Africa have been experiment-based and have mostly targeted conservation areas where fire is managed. However, it is vital to have an in-depth knowledge of fire effects on vegetation and soil as it pertains to the real-life situation in rural areas. This would bring to fore the species that are adapting, added or lost to the frequent fires in the savannas of Africa. There is also, a need for a comparison of the effects of fire on species in protected and unprotected landscapes. The is an increasing changing trend in land uses where fallow periods for instance is decreasing resulting in the increasing in burning of biomass to add ash to the soil for crop production. Charcoal burning which is becoming and alternative source of income to crop farming due to the changing climates and erratic rainfall patterns needs attention. It is another prominent use of fire in these savannas but which has received very little attention. There is, however, a possibility of a broader stakeholder consultation to address the issues of fire use in agroforestry parkland for sustainability.

Given the cumulatively large areas that are burnt in rural regions of Africa, it will not be representative enough to generalise effects of fire based on protected areas and experiments where fire is very regulated. This research highlights the importance of user-centred research for policy recommendations that would ensure sustainable management and conservation of natural and environmental resources. Thus, for such complex ecological systems as agroforestry parklands of Ghana and West Africa, a five-tier SES framework would be a holistic approach that can aid in ensuring resilience and sustainability of these systems. Thus, the next line of action for further research would have to integrate other formal institutions (actors) and the governance systems in the management of these parklands.

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