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The impact of bushfire on carbon and nutrient stocks as well as albedo in the savanna of northern Ghana

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To my parents (Father-the late Patrick Konlaan Bagamsah and Mother Hawa Bagamsah) for the great decision they made to send me to school, and to my wife Cynthia and son Yoobaar.

ABSTRACT

In savanna systems of northern Ghana, bushfire is a common phenomenon that has a major impact on ecosystem structure and functioning. The combination of a hot, dry season with the accumulation of readily combustible dry plant material makes much of the area extremely prone to the impact of bushfires. Bushfires have been identified as one of the causes for the decline in soil fertility in the last two decades in northern Ghana.

The overall objective of the study is to quantify nutrient fluxes due to bushfires in the savanna landscape of northern Ghana. Specifically, the study is to describe the heterogeneity of the vegetation structure and quantify carbon and nutrient losses due to bushfires. Furthermore, it is to estimate carbon emissions and finally to assess the impact of bushfire on albedo and soil surface temperature.

The study was conducted within the Guinea Savanna Agro-Ecological Zone of Ghana as part of the on-going Glowa-Volta research project. It lies between the latitudes 8^{o} 30'N and 10^{o} 30'N and the longitudes 2^{o} 30'W and 0^{o} 00'W.

Satellite images show 5 broad land-cover and land-use types in the study area. Most of the sites were categorized under the widely open savanna woodland. Field observations indicate that there are actually no pure stands in the study area but rather a mixture of grasses, shrubs and trees. The vegetation heterogeneity of the study area was described using the Dansereau methodology.

The nutrient concentrations were variable across the different vegetation types and fuel components, but did not show any particular trend. The nitrogen concentration was higher in leaves and litter than in twigs and ranged from 3.0 – 8.7 mg g^{-1}. Carbon concentration ranged from 42 - 50 % among the fuel load components.

The nitrogen and carbon concentrations in ash were lower than in the fuel. Conversely, concentrations of P, K, Na, Ca, and Mg were higher.

The quantity and quality of the fuel load is influenced by the vegetation cover type. The highest fuel load measured was 7.8 t ha^{-1} in the grass savanna, with grass being the dominant fuel and contributing over 60 % of the total fuel load.

The total nutrient stock is correlated to the quantity of the fuel load. Typically, grass and grass/tree savanna sites recorded significant N stocks (26- 27 kg ha^{-1}); the lowest N stocks (14 kg ha^{-1}) were recorded in the grass/shrub savanna. In all the sites, 26 - 97% of all nutrients in the fuel load were transferred to the atmosphere during the bushfire. The net losses of N, P and K during annual bushfires in the study sites were estimated to be approximately 10 – 22 kg ha^{-1}, 1-7 kg ha^{-1} and 2-12 kg ha^{-1}, respectively.

The highest amount of gas emitted from the mapped burnt areas was CO_2, ranging from 3 x 10^4 to 5 x 10^4 tons and the lowest was N_2O, between 2.2 to 5.2 tons across vegetation types. Additionally other gases emitted include; CO 2 x 10^3 – 4.8 x 10^3 ton and CH_4, 92 – 216 tons. The cumulative total of CO_2 emissions for all vegetation types was 1.7 x 10^5 tons. The cumulative total of CO_2 emissions from all sites was 1.7 x 10^5 tons.

Seasonal and bushfire-induced shifts in albedo affect the amount of net solar radiation (net short wave radiation) retained at the surface of the soil. The high post-fire soil surface temperature observed is due to the high net absorbed solar radiation as a result of lower albedo, increasing the sensible heat flux, since evapotranspiration is lower.

Generally the study concludes that in the nutrient-poor savannas of northern Ghana, long-term effects of repeated bushfires on the ecosystem can lead to serious net losses of N. Furthermore, the present study suggests that biological fixation and wet depositions may be of insufficient magnitude to replace the lost N. To reduce the likelihood of progressive land degradation, the use of fire in land preparation would need to be reduced.

Der Einfluss von Buschfeuer auf Kohlenstoff- und Nährstoffvorräte sowie die Albedo in der Savanne Nord-Ghanas

KURZFASSUNG

In den Savannengebieten Nord-Ghanas sind Buschfeuer häufig auftretende Ereignisse mit tief greifenden Auswirkungen auf Struktur und Funktion des Ökosystems. Die überwiegende Mehrzahl der Buschfeuer ist anthropogenen Ursprungs und tritt in der heißen Trockenzeit auf, wenn sich große Mengen leicht brennbaren Pflanzenmaterials angesammelt haben. Buschfeuer werden als einer der Gründe für die Abnahme der Bodenfruchtbarkeit in Nord-Ghana angesehen.

Gegenstand der vorliegenden Arbeit sind die Nährstoffflüsse in der Savannenlandschaft Nord-Ghanas in Verbindung mit Buschfeuern. Im Einzelnen wird die Vegetationsstruktur der Savannenstandorte beschrieben und deren Kohlenstoff- und Nährstoffvorräte sowie -verluste durch die Buschfeuer quantifiziert. Außerdem werden die Kohlenstoffemissionen und die Bedeutung der Buschfeuer auf Albedo und Bodenoberflächentemperatur ermittelt.

Die Untersuchung wurde innerhalb der Guinea-Savanne von Ghana als Teil des "Glowa-Volta"-Forschungsprojektes durchgeführt. Das Untersuchungsgebiet liegt zwischen den Breitengraden 8^o 30’N und 10^o 30’N und den Längengraden 2^o 30’W und 0^o 00’W.

Satellitenaufnahmen zeigen fünf Landbedeckungs-/Landnutzungstypen im Untersuchungsgebiet. Die meisten Standorte wurden als offener Savannenwald charakterisiert. Felderhebungen zeigen, dass keine reinen Baumbestände vorkommen, sondern i.d.R. eine Mischung aus Gräsern, Sträuchern und Bäumen. Die Vegetationsstruktur des Untersuchungsgebietes wurde mit Hilfe von Danseraus Methode beschrieben.

Die Nährstoffkonzentrationen variieren in den verschiedenen Vegetationstypen und Komponenten der brennbaren Biomasse, allerdings ohne erkenntlichen Trend. Die N-Konzentrationen lagen zwischen 3,0 und 8,7 mg g^{-1} und waren in den Blättern und in der Laubstreu höher als in Zweigmaterial. Die Kohlenstoffkonzentrationen lagen zwischen 42 und 50%, abhängig von der Biomassekomponente.

Die C- und N-Konzentrationen waren in der Asche niedriger als in der brennbaren Biomasse, die Konzentrationen von P, K, Na, Ca und Mg dagegen höher.

Die Quantität und Qualität der brennbaren Biomasse hängt von der Vegetationsdecke ab. Der höchste Wert für brennbare Biomasse wurde mit 7,8 t ha^{-1} in der Grassavanne ermittelt, wobei Gras mit 60% den größten Anteil zur brennbaren Biomasse beitrug.

Der Gesamtnährstoffgehalt einer Vegetation korreliert mit der brennbaren Biomasse. Die Gras- und Gras/Baumsavannenstandorte hatten die höchsten N-Vorräte (26-27 kg ha^{-1}), Gras/Buschsavannenstandorte die niedrigsten. Unabhängig vom Standort wurden 26 - 97% der Nährstoffevorräte der brennbaren Biomasse während des Feuers in die Atmosphäre abgegeben. Die Nettoverluste (Brennverluste abzüglich atmosphärische Einträge) von N, P, und K betrugen 10-22, 1-7 bzw. 2-12 kg ha^{-1}.

Bei den Gasemissionen durch Buschfeuer liegt CO_2 an erster Stelle. Durch Brände werden aus den einzelnen Untersuchungsgebieten jährlich zwischen 3 x 10^4 und 5 x 10^4 t CO_2 emittiert. Die niedrigsten Werte wurden für N_2O ermittelt: 2,2 – 5,2 t.

Kohlenmonoxid liegt bei 2 x 10^3 bis 4,8 x 10^3 t, Methan bei 92 – 216 t. Insgesamt werden aus den erfassten Flächen des Untersuchungsgebietes 1,7 x 10^5 t CO_2 pro Jahr durch Buschfeuer in die Atmosphäre freigesetzt.

Eine veränderte Albedo aufgrund saisonaler Veränderungen der Vegetation und Buschfeuer beeinflusst die Höhe der Nettoeinstrahlung an der Bodenoberfläche. Die erhöhte Temperatur der Bodenoberfläche auf gebrannten Flächen ist Folge der absorbierten Strahlung durch niedrige Albedo. Hierdurch wird der fühlbare Wärmefluss erhöht, da die Evapotranspiration niedriger ist.

Es wird geschlussfolgert, dass durch die alljährlichen Buschfeuer die nährstoffarmen Savannen Nord-Ghanas beträchtliche N-Verluste erleiden. Die biologische N-Fixierung und der atmosphärische Eintrag reichen nicht aus, die N-Verluste auszugleichen. Um eine fortschreitende Landdegradation zu vermeiden, muss der Einsatz von Feuer in der Landnutzung reduziert werden.

TABLE OF CONTENTS

ABBREVIATIONS AND ACRONYMS

SOM	Soil Organic Matter
NOAA	National Oceanic and Atmospheric Administration
AVHRR	Advanced Very High Resolution Radiometer
SPOT	Satellite Pour l´observation de La Terre
TM	Thematic Mapper
MSS	Multi - Spectral Scanner
ITCZ	Inter-Tropical Convergence Zone
GLOWA	Globaler Wandel des Wasserkreislaufes (Global Change in Hydrologic Cycle)
ARI	Animal Research Institute
SARI	Savanna Agricultural Research Institute
GPS	Geographic Positioning System
RGB	Red Green Blue
ENVI	Environment Visualizing Image
EPA	Environmental Protection Agency
MOFA	Ministry of Food and Agriculture
BATS	Biosphere-Atmosphere-Transfer Scheme
SRI	Soil Research Institute
GMT	Greenwich Mean Time
SSA	Sub-Sahara Africa
DAAD	German Academic Exchange Service
CSIR	Council for Scientific and Industrial Research
ZEF	Center for Development Research

1 INTRODUCTION

1.1 Background

Bushfires are uncontrolled fires occurring in the rural landscape (Cheney, 1981). In the savannas of Ghana, bushfires, which are mostly man-made, are very common. These fires are typically grass fires and their intensity is usually lower than that of the forest fires. Fire is a major landscape-scale perturbation in many ecosystems throughout the world (Johnson, 1992; Pyne et al., 1996), but it is especially frequent in the tropical savanna (Goldammer 1990; Andersen et al., 1998). Nevertheless, its cumulative effect has a major impact on the ecosystem functioning.

Fire is the most devastating factor contributing to loss of vegetation, nutrients and especially to natural resource degradation in the savannas of Ghana. Ravaging annual bushfires have reduced the vegetation of the region to the level that can be described as fire-pro-climax, with only fire-resistant species surviving. The densities and mix of tree species vary widely in the more highly degraded areas, with (woody) grassland vegetation dominating (Ekekpi et al., 2000).

During biomass combustion, nutrients can be volatilized or transferred to the atmosphere as particulate matter (Cook, 1992). The particles are likely to be deposited on or near the site of fire, but this is not the case for volatile elements such as carbon and nitrogen. Nutrients remain on the ground in ash and other residue after the fire along with the deposited particles, which are highly susceptible to erosion through runoff (Gillon, 1983; Kellman et al., 1985) and wind.

Additionally, frequent fires have deleterious effects on the nutrition of the savanna plant communities, which grow on nutrient-poor soils with low rates of natural nutrient input. The losses in vegetation and nutrients can lead to loss of watershed protection, leading to drying of rivers, soil degradation and severe impacts on the entire savanna ecosystem.

Bushfires have been identified as one of the causes of the decline in soil fertility in the last two decades in northern Ghana (Abatania and Albert, 1993; Gordon and Amatekpor, 1999). Bushfires thus impact negatively on savanna agro-ecological zones leading to degradation of the soils. This is particularly so for the soils within Sub-Sahara Africa (SSA) which are very fragile and easily degraded and deteriorating at an alarming rate (Vlek, 1993). Comparison of soils in sacred groves with the annually burnt soils shows marked differences in soil quality. For example, the soil in the Chicago sacred grove near Tamale had 13.1 % soil organic matter (SOM), whereas the annually burnt soil on the Tamale-Bolga road a few kilometers away had an SOM content of only 1.8 % (Korem, 1989). More importantly, the process of laterization in the fire-protected grove is much slower than in the annually burnt areas, mainly due to a much higher organic matter content (Korem, 1989).

At a regional scale, savanna fires have significant impact on the regional water, energy, and carbon dioxide exchanges (Lynch and Wu 2000, Beringer et al., 2003) and as a result are likely to have important feedbacks on the atmosphere and regional climate and hydrology. Large variations in the Earth surface reflectance (albedo) occurring over savanna areas of Africa could not be explained by changes in vegetation cover between the wet and dry season and bushfires have been implicated.

The current study has its relevance particularly to savanna zones of Ghana because of the vulnerability of the environment and the concomitant high impact of bushfires. Specific scientific information emanating from this study will assist in developing the right policy framework for bushfire management and overall environmental management.

1.2 Research objectives

Losses of the various carbon and nutrient components of the savanna ecosystem as a result of bushfires have so far not been quantified in the savanna zones of Ghana. The overall objective of this study therefore is to quantify nutrient fluxes due to bushfires in the savanna landscape of northern Ghana.

The specific objectives of the study are:

1) Characterization of the savanna vegetation in the study area
2) Determination of fuel load as well as carbon and nutrient losses due to bushfires
3) Estimation of carbon emissions
4) Assessment of the impact of bushfire on albedo and surface energy fluxes

2 STATE OF KNOWLEDGE

Bushfires are an annual occurrence in the Guinea Savanna of Northern Ghana. They start soon after the rainy season and are characterized by widespread devastation.

The whole area is covered with a mantle of ash and the trees and shrubs are leafless and have charcoal blackened barks.

Generally, there are two major causes of bushfires. These are natural and anthropogenic. The natural cause is through ignition by lightning. Some far-fetched reasons have also been reported though, such as sparks from falling rocks and exploding fruits (Langaas, 1995). However, it is assumed that almost all fires are ignited by humans (Korem, 1985).

The effect of bushfires stems not only from its pervasiveness in modifying the environment, but also from the extensiveness of the area affected in proportion to the human effort applied. Rural inhabitants use fire to facilitate many activities associated with daily life. The most commonly cited causes of bushfires in the study area are: burning to clear lands for agriculture, to improve pasture land by removing unpalatable stubble and initiating off-season regrowth, eliminating reptiles and pests, to drive game for hunting, for tapping honey and charcoal production. The impacts of frequent bushfires include: destruction of the vegetation, soil degradation, nutrient losses, shifts in albedo, contribution to greenhouse effect and global warming.

2.1 Savanna fires and emissions

Savanna is broadly defined as a tropical physiognomic vegetation type consisting of a continuous grass stratum usually with a discontinuous stratum of trees or shrubs. It occupies about 20% of the Earth's land surface (Cole, 1986; Stott, 1991). In their natural state, savannas can support a high biomass of large ungulates (Cumming, 1982; Walker and Noy-Meir, 1982), but most have been exploited for agriculture, livestock grazing or destroyed by bushfires. Because of intensive overstocking, fuel-wood harvesting and shortened fallow periods between cropping periods, savannas, especially those in Africa, are undergoing rapid changes in vegetation productivity, structure and composition (Walker and Noy-Meir 1982; Jansen, 1988; Lewis and Berry, 1988).

Bushfires emit significant amounts of carbon dioxide (CO_2), carbon monoxide (CO), nitrous oxide (NO_2) and methane (CH_4) into the atmosphere. The annual flux from the world's CO_2 from African savanna burnings has been estimated to equal 30% of the annual flux from the world's industrial sources (Hao et al., 1996).

Changes in the savanna areas may affect the global climate and atmospheric trace gas composition, surface energy balance and hydrological and biogeochemical cycles (Olsson 1985a; Levine, 1991). Some of these effects are already apparent; for example, African savanna fires, almost all resulting from human activities, may produce as much as a third of the total global emissions from biomass burning (Hao et al., 1990; Cahoon et al., 1992; Stott, 1994).

2.2 Fuel load and nutrient losses

Fuel load is the amount of combustible vegetation available for burning, which is determined by the type and amount of vegetation. In the West African savanna environment, the available plant biomass for fire (only counting the grassy biomass) varies from an average 0.5 t ha^{-1}, some local areas having over 10 t ha^{-1} (Menaut, 1983; Goldammer, 1993; Rasmussen, 1998). In the Kruger National Park, it was found that the fuel loads varied between 0.32 and 4.5 t ha^{-1} (Trollope et al., 1996). Results of mean fuel load (grass) from the savannas of Northern Ghana by Saarnak (1999) ranged between 2 and 3 t ha^{-1}. The total fuel load in tropical savanna vegetation was between 3.8 and 4.15 t ha^{-1}, and 6.3 t ha^{-1} in a study by Cook (1994). Similar results of total fuel load of 3 t ha^{-1} were recorded in the savanna of Venezuela by Hernandez-Velencia and Lopez-Hernandez (2002). Brookman-Amissah (1980) reported grass biomass at the end of growing season of 1.8 t ha^{-1} on protected plots, and 2.6 t ha^{-1} and 1.4 t ha^{-1} on early and late bushfire plots respectively in northern Ghana.

Burning of the vegetation can have catastrophic effects on ecosystem productivity. Fire affects the organic matter of the vegetation and litter in several ways. It directly consumes part or all the standing aboveground plant material and litter. When vegetation burns, it liberates nutrients tied up in the plant tissues. Portions of the elements contained in the combusted material are transferred to the atmosphere and transported over long distances in smoke plumes and thus lost to the immediate environ (Evans and Allen, 1971; Smith and Bowes, 1974; Raison, 1979; Mackensen et al., 1996). Air currents and updrafts during fire carry particles of ash and these remove nutrients from the site.

Transfers of nutrients to the atmosphere during the annual burning in the savanna of Congo amounted to 85%, 25%, 39%, 21% and 28% of the amounts of N, P, K, Ca and Mg, respectively, accumulated in the aerial biomass and litter component (Laclau et al., 2002). In a similar work done in the savanna region of Calabozo, Venezuela, about 95% of the biomass, 97% of N, 61% of P, 76% of K and 65% of Ca and Mg were transferred to the atmosphere. Ash deposition returned between 21-34% of Mg, Ca, K and P and 0.2% of N. As a consequence of frequent burning, the soil of the savanna showed lower organic matter and available P and K content when compared to 32-year protected savanna (Hernandez and Lopez, 2002). Estimates from the work of Vijver (1999) in East African savanna systems indicate that the loss of nutrients through volatilization was as follows; N 93%, P 32%, K 60%, Ca 42% and Mg 12%.

Nutrient losses reported by Sommer (2000) in woody fallow vegetation were, 96%, 98%, 90%, 58%, 59%, 70% and 89% for C, N, P, K, Ca, Mg and S, respectively. Element transfer to the atmosphere due to burning through particle transport and volatilization were 94-98% C, 95-98% N, 27-33% P, 17-23% Na, 16-31% K, 9-24% Ca, 17-43% Mg, and 67-68% S of the initial element stock in the burnt debris in the Amazonia secondary forest (Mackensen et al., 1996). Trabaud (1994) estimated that losses of N, C and P from combustible plant matter woody scrub exceeded 98%, 97% and 79%, respectively.

Preliminary analysis (Cook, 1992, 1994) of data on the effects of fire on the savannas indicates that annual fires might result in the net losses of nitrogen, and possibly also potassium and magnesium from the ecosystem. Estimated rates of biological fixation of nitrogen appear to be insufficient to replace the annual losses of this element. It is therefore concluded that a regime of annual fires that completely burn the available grassy fuel would deplete nitrogen reserves in savanna, unless there are other sources of biologically fixed N, which are unknown at present (Cook, 1994).

2.3 Effect of fire on soil

Wildfire can lead to detectable losses of mineral soil N as demonstrated by Grier (1975), who noted significant losses (855 kg ha^{-1} of N and 282 kg ha^{-1} of K) from an intense wildfire. Nitrogen losses due to wildfire ranged from 0 kg ha^{-1} in black spruce (*Picea mariana*) forest (Dyrness et al., 1989) to 855 kg ha^{-1} in mixed coniferous forest (Grier, 1975). Prescribed fire can cause as much N loss as wildfire: nitrogen losses due to post-harvest slash burning range from an apparent gain of 192 kg ha^{-1} yr^{-1} to a net loss of 666 kg ha^{-1} yr^{-1} (Little and Ohmann, 1988). In a comprehensive review of N losses due to slash burning in British Columbia, Feller (1982) reported N loss values ranging from 7 to 604 kg ha^{-1} yr^{-1}.

Methods for classifying burns based on litter and soil appearance after a fire have been described by Wells et al., (1979) and Chandler et al., (1983). Low intensity or lightly burned areas are characterized by black ash, scorched litter and duff, low plant mortality, and maximum surface temperatures during burning of 100 to 250^{o}C. Moderate burning produces surface temperatures of 300 to 400^{o}C and consumes most of the plant materials, thus exposing the underlying soil, which otherwise is not altered. High intensity or severe burning produces surface temperatures in excess of 500^{o}C, and can be recognized by the white ash remaining after the complete combustion of heavy fuel and the reddening of the soil. Sertsu and Sanchez (1978) found that heating three soils to 400^{o}C in the laboratory resulted in redder hues and brighter chromas. Boyer and Dell (1980) also described a blackened layer underlying the reddened soil in a severely burnt area. They suggested that the black color is due to the charring of organic matter by heat conducted through the top layer of the soil during fire.

Soil texture changes have also been observed in response to fires and laboratory heating. Dyrness and Youngberg (1957) found a significant decrease in the clay content of severely burned soils and a corresponding increase in sand, suggesting the aggregation of clay-sized particles into stable and sand-sized secondary particles. Similar results were noted by Sreenivasan and Aurangabadkar (1940) in that the decreased clay content corresponded with increased silt and fine sand content in fire-heated Vertisols. Ulery and Graham (1993) confirmed that the particle size distribution shift was due to the fusion of clay into sand-sized particles. Laboratory heating to 400^{o}C also significantly reduced the clay fraction of chaparral soils from southern California (Duriscoe and Wells, 1982) and of Vertisols from India (Puri and Asghar, 1940) and Ethiopia (Sertsu and Sanchez, 1978).

Frequent burning can reduce the rate of infiltration of rainwater into soil (Phillips, 1930; Daubenmire, 1968; Schacht et al., 1996; Bijker et al., 2001). This may be explained as follows: Firstly, soil organic matter, which usually increases soil aggregation and consequently the rate of infiltration (Dyrness and Younberg, 1957;

Pikul and Zuzel, 1994; Cook et al., 1992), tends to decline in soils that are burnt frequently (Bird et al., 2000). Secondly, ash particles may block pores at the soil surface (Mallik et al., 1984). Thirdly, the removal of vegetation increases the exposure to raindrops, which would increase breakdown of aggregates, dispersion of clay and thus soil crusting (Hillel, 1998). Results reported by Mills and Frey (2004) conclude that soil from 0-1cm in burnt plots had lower total carbon (means of 0.8 % vs. 2.7 % for burnt and unburnt plots, respectively), total N (0.07 % vs. 0.23 %), (NH_4)OAc-extractable Ca (7 vs. 17 mmol kg^{-1}), Mg (2 vs 7 mmol kg^{-1}), K (0.8 vs. 1.5 mmol kg^{-1}), and greater exchangeable Na percentage (17 % vs. 8 %). The results also indicate that burning increases soil crusting.

2.4 Fire effect on albedo and surface energy fluxes

Albedo is the fraction of the total incident solar radiation that is reflected by a body or surface. Land surface albedo is a key parameter in the global system. It quantifies the radiometric interface between the land surface and the atmosphere. It influences the climate system and defines the shortwave energy input into the biosphere. Natural and anthropogenic changes in vegetation and land use practices affect the spatial, temporal and spectral distribution of its value.

Extensive and frequent fires in the savannas are intensive in the late dry season and cause crown damage of > 90 %. The scorched canopy reduces the leaf area index (LAI) of the canopy and these surface changes are likely to result in altered energy partitioning (enhanced sensible heat flux) and shifts in albedo. A fire event also causes a loss of functional canopy leaf area and subsequent reduction in canopy, photosynthesis and evapotranspiration, greatly influencing post-fire fluxes (Beringer et al., 2003).

Fire in the savanna is likely to radically alter the surface energy through reduced albedo. The pre-burn albedo of the savanna sites were 0.11 and 0.12 for low and moderate intensity burns, respectively. Following fire, the flat savanna surface was blackened and became highly absorptive. Albedos were reduced to almost half at the study sites to 0.06 and 0.07, respectively (Beringer et al., 2003).

Scholes and Walker (1993) also reported a halving of the African savanna albedo to 0.06 immediately following fire, with a recovery to unburnt values after six weeks. The effect of burning on flooded stands decreases the average daily albedo from 0.16 for an unburned stand to 0.08 in the burned stand, whereas the effect of flooding on the average daily radiative budget for the burned stands decreased the average daily albedo from 0.14 for the unflooded stand to 0.08 for the flooded stand (San Jose et al., 2001).

Recent studies have shown that roughness length, plant insolation factor, vapor pressure deficit factor, leaf area index, surface albedo, surface emissivity, fractional vegetation coverage, soil field capacity, wilting point and minimum stomatal resistance are the most important land surface parameters (Avissar et al., 1989; Bastiaanssen, 1995; Deardoff, 1978; Noilhan et al., 1989). However, only albedo will be considered in this study because of its relevance to bushfire. Albedo changes control the capacity of terrestrial surfaces to reflect or absorb solar radiation and, therefore, influence the amount of energy available near the surface, as well as its release to the atmosphere (or to lower soil layers) as latent and sensible heat. It is well known that the energy balance on the surface plays a major role at seasonal and interannual time scales. Changes in land surface albedo occur naturally as a result of climate variability and phenological stages of growth and development in vegetation. However, they may also result from anthropogenic activities that modify landcover, such as bushfires, deforestation, reforestation, and agriculture.

2.5 Satellite remote sensing and estimation of burnt areas

Fire activity results in two primary signatures that can be detected via remote sensing (Wooster, 2001). The first detectable fire signature is active burning, which, due to its high temperature, emits a strong irradiative signature in the visible and infrared region of the electromagnetic spectrum.

The second fire signature is that of burnt scars left by the passage of the fire, which are generally much darker in the visible and near-infrared wavelengths than the surrounding still-vegetated areas because of the destroyed vegetation and the layer of ash (Wooster, 2001).

A reliable method to assess burnt areas is by using high resolution images such as SPOT HRV and Landsat TM images (Bourgeau-Chavez et al., 1997; Eastwood et al., 1998; Kasischke et al., 1992; Mbow et al., 1999; Saarnak et al., 1999c). Other quantitative analyses using satellite Earth observation, especially the NOAA AVHRR sensor, have proven useful for the purpose of detecting active fires (Herland et al., 1997;

Justice et al., 1996; Belward et al., 1994; Langaas, 1993b; Frederiksen et al., 1990). Using the thermal AVHRR channel of 3 high intensity fires as small as 10 m x 10 m can be detected (Langaas, 1993a; Prins & Menzel, 1992; Brustet et al., 1991). However, detecting the relatively small agricultural fires is difficult due to the short overpass time of the satellite. However, a quantitative study could be carried out using high spatial satellite imagery, such as Landsat TM or SPOT (Nielsen and Rasmussen, 1997).

Landsat imagery [Multispectral Scanner (MSS) and current Thematic Mapper (TM)], which shows < 0.5 and < 0.1 ha, respectively, but has infrequent satellite passes (16 and 18 days, respectively) has been used to calibrate more coarse-scale imagery with daily return times (Eva and Lambin, 1998; Elvidge et al., 2001; Fuller and Fulk, 2001). Indeed, the fine scale of Landsat imagery is often seen to out-weigh the disadvantage of the sporadic availability of cloud and haze-free images for the production of fire-scar maps (Bowman et al., 2003).

Imperfect temporal coverage of Landsat imagery during a burning season is of little concern in many landscapes, because fires are infrequent phenomena and the slow rate of vegetation recovery makes fire scars enduring and conspicuous landscape features (e.g. Minnich, 1983; Turner et al., 1994; Haydon et al., 2000). Unfortunately, this is not the case for the most fire-prone environment on Earth, savannas in the seasonal tropics (e.g. Dwyer et al., 2002), where recovery can obliterate fire scars within a fraction of the burning season (e.g. O' Neill et al., 1993; Eva and Lambin, 1998; Trigg and Flasse, 2000). Such rapid recovery of burnt tropical savanna vegetation renders maps of fire scars in these landscapes of uncertain reliability (Eva and Lambin, 1998) and can confound sophisticated analyses of fire-scar data (Gill et al., 2000).

There is no consensus as to which is the most appropriate methodology to map fire scars from satellite imagery (e.g. Brieb et al., 1996; Eva and Lambin 1998; Fuller 2002; Salvador et al., 2000; Trigg and Flasse, 2000). Of particular importance is the capacity to reliably discriminate burnt areas regardless of the date of the satellite image or the timing of the fire during the burning season (Viedma et al., 1997; Eva and Lambin,1998; Trigg and Flasse, 2000). The reliability of fire scars is typically measured by determination of omission or commission errors using a diversity of data sources such as: ground truthing during a limited time period, official fire mapping records, the information from local residents and land managers, or combinations of these (Russel-

Smith et al., 1997; Giri and Shrestha, 2000; Salvador et al., 2000; Edwards et al., 2001; Rogan and Yool 2001; Romas'ko et al., 2001).

In the tropical savanna of northern Australia, Bowman et al. (2003) evaluated four methods to map fire scars apparent on Landsat-TM imagery: systematic visual, semi-automated, automated and change detection. All methods showed rapid fading of the fire scars. Generally automated and visual methods were able to discriminate burnt areas better than other methods. However, the automated method also falsely identified fire scars on between 5 and 20% of the unburnt catchments prior to the experimental late dry season treatments. One cause of fading appears to be related to increased flushing of tree canopies on burnt areas, although the spatially patchy recovery within and between catchments points to the importance of other factors such as the recovery of the ground layer. It appears that Landsat-TM imagery cannot be used to reliably determine the spatial extent and timing of fires in environments with rapid post-fire recovery, such as tropical savannas, thereby limiting the utility of this data source for fine-scale ecological studies.

3 GENERAL DESCRIPTION OF THE STUDY AREA

3.1 Location

The study was conducted in the Northern Region in Ghana, which represents one of the 10 administrative regions (Figure 3.1). The population of this area is about 1.7 million and represents 9.6 % of the entire population of Ghana (Ghana Statistical Service, 2002). It lies within the Guinea Savanna Agro-Ecological Zone and forms part of the Volta Basin, and lies between the latitudes 8^{o} 30’N and 10^{o} 30’N and the longitudes 2^{o} 30’W and 0^{o} 00’W.

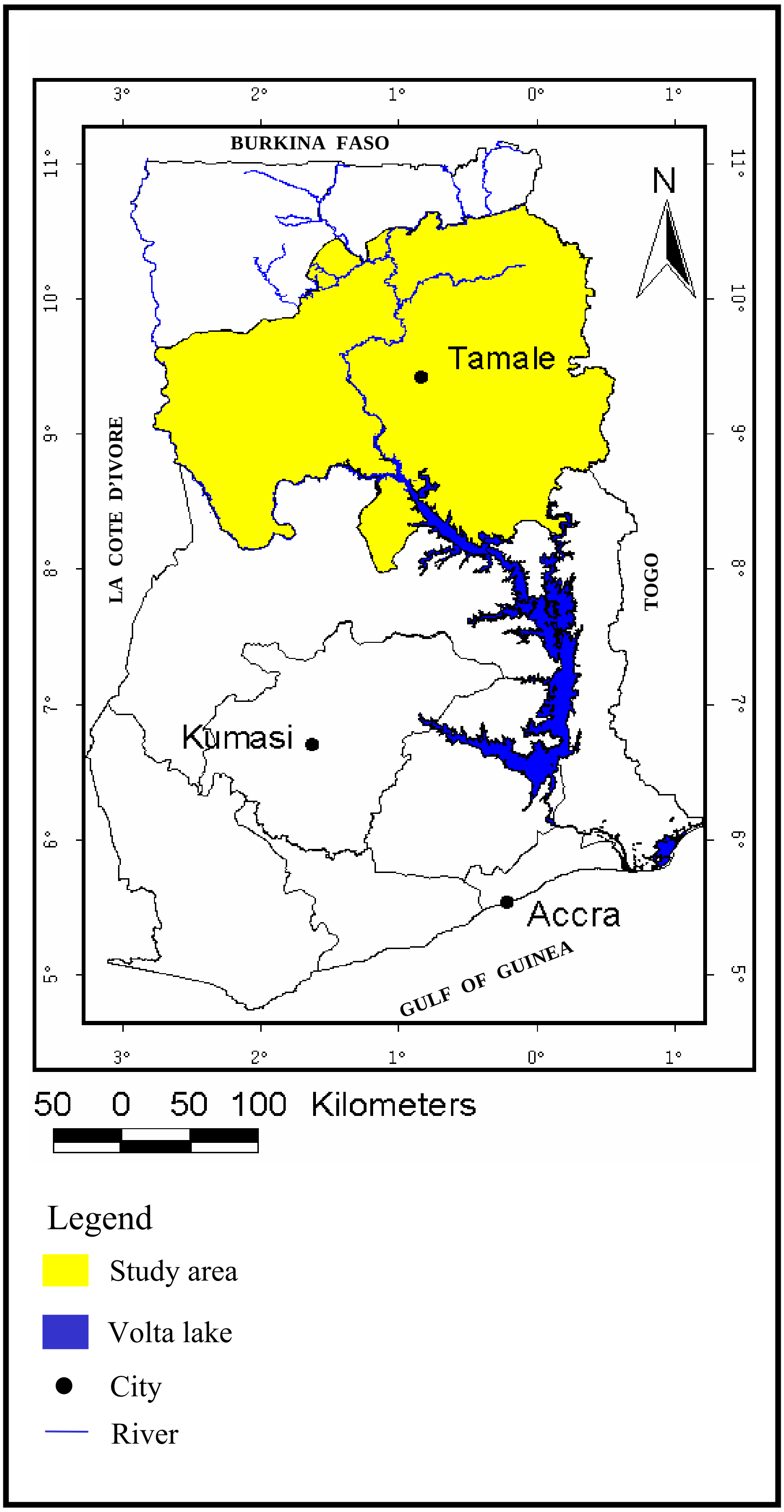


Figure 3.1: Location of Northern Region (shaded) in Ghana

3.2 Climate

The climate of the Guinea Savanna is semi-arid with an annual monomodal rainfall pattern, annual average rainfall lying between 1000 and 1200 mm (Kasei,1993; Runge-Metzger and Diehl, 1993) throughout the region. The length of the dry season varies from five to six months (November to April), while the wet season is six to seven (May to October), with the effects of the harmattan increasing from south to north. Rainfall reliability lies between 12 and 16 % of average values and large deviations from monthly and annual means are common (Rose Innes, 1977).

Characteristically, the area has a long dry season starting in November and ending in April during which time rainfall is limited to rare scattered showers. The days are hot with little cloud and scorching sunshine and the night relatively cold with light winds. In the rainy season, rains reach a peak in August and September and after that there is another but much shorter period of thunderstorm and rainfall up to the onset of the following dry season in November.

Temperatures are generally high with mean monthly maxima and minima of 35°C and 22°C (Figure 3.2), not varying widely (Rose Innes, 1977); the mean temperature is about 28°C with potential evaporation of 1500 – 1800 mm (Kasei, 1993).

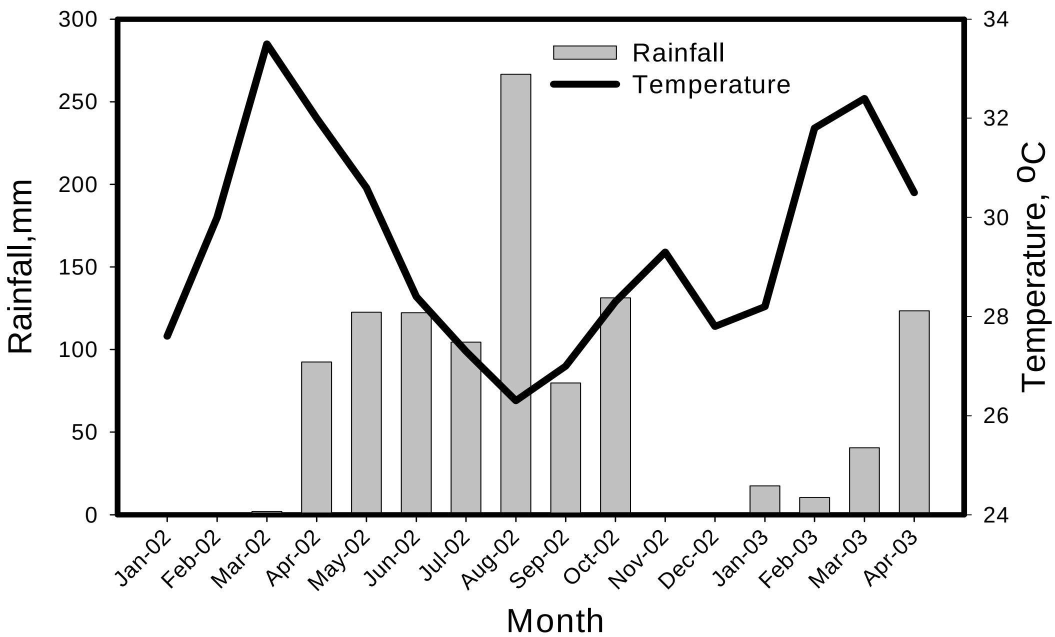


Figure 3.2: Mean monthly rainfall and temperature measured at weather station in Tamale, January 2002 – April 2003

3.3 Soil

The major soil groups are Lixisols, Leptosols, Plinthsols, Acrisols and Luvisols (FAO, 1988). Furthermore, extensive areas are covered by groundwater lateritic soils, which have developed over both the Voltaian shales and granites. The principal characteristic is the presence at generally shallow depths below the surface of the soil of a more or less cemented layer of ironstone, called iron pan, through which rainwater does not penetrate easily. In color, the soils range from combinations of yellow and brown to yellow and grey; the texture is silty or sandy loam if the soils are developed over the Voltaian shales, or coarse sandy loam if developed over the granites (Benneh and Dickson, 1988).

The topsoils are mostly, sandy and the gravel content increases with depth (Hauffe, 1989). The soils are characterized by widespread lateritic concretions (Owusu-Bennoah et al., 1991). They have low aggregate stability and are extremely susceptible to surface sealing by rains and also to soil erosion. However, during the wet seasons these soils have the advantage of a good drainage (Hauffe, 1989).

The different hydrological conditions along the slopes lead to the development of different soils from the upland to the lowland. In the study area, soils are mostly upland soils developed in-situ from Voltaian sandstone, occupying about 80 % of the studied sites. These soils are classified under the group of Lixisols (FAO, 1988).

In general, the soils of the region have a much lower organic matter content and nutrient status than forest soils. Over large areas, the soils have unfavorable moisture relationships and, in addition, the rainfall is less reliable than in the forest zone. The potential productivity of the soils of this zone must on the whole be regarded as appreciably lower than that of the majority of the forest zone (Wills, 1962).

3.4 Vegetation

Vegetation is a function of rainfall, edaphic factors, geomorphology, fire occurrence rates and differential grazing pressures (Milich and Weiss, 2000). In the study area, the characteristics of the vegetation have been determined by its rainfall, soil and the anthropogenic influence (Lane, 1962). In the vegetation map of Ghana (Figure 3.3), the vegetation of the study area is seen to be largely mid-dry savanna with patches of dry savanna and wet savanna (Menz and Bethke, 2002). The mid-dry savanna and dry savanna are classified under Guinea savanna (Taylor, 1952; Baker, 1962; Hopkins 1981 and Lawson, 1985).

The characteristic vegetation cover of the zone is the woodland savanna, which consists of open stands of trees, the crowns of which form a canopy, and a ground cover of herbaceous tussock grasses up to 2 m high. The crowns of adjacent trees are often in contact but not densely interlocking as in forest vegetation.

The natural vegetation includes trees of the species *Daniellia oliveri, Lophira alata, Terminalia glaucescens, Guiera senegalensis, Combretum glutinosum, Piliostigma reticulate, Parkia biglobosa* and *Vitellaria paradoxa*

Most vegetation is found in various stages of regeneration following periods of cultivation. Where the fallow period is short and fires are frequent, the trees are often represented by coppice of shoots and mature trees of especially preserved species of economic importance: *Parkia sp*, *Butyrispermum parkii* (karate), *Faidherbia albida*, *Tamarindus indica* (tamarind), and *Ceiba pentandra* (kapok), *Parkia biglobosa and Vitellaria paradoxa*. The grasses are mostly annual because of the drought stress in the long dry period. Commonly occurring annuals include: *Andropogon sp, Cymbopogon sp, Pennisetum sp,* and *Settaria sp.* Furthermore, a number of perennials grow vigorously: *Andropogon gayanus, Anthrophora nigritane, Aristida stipoides, Pennisetum setosum,* and *Hyparrhenia sp.*

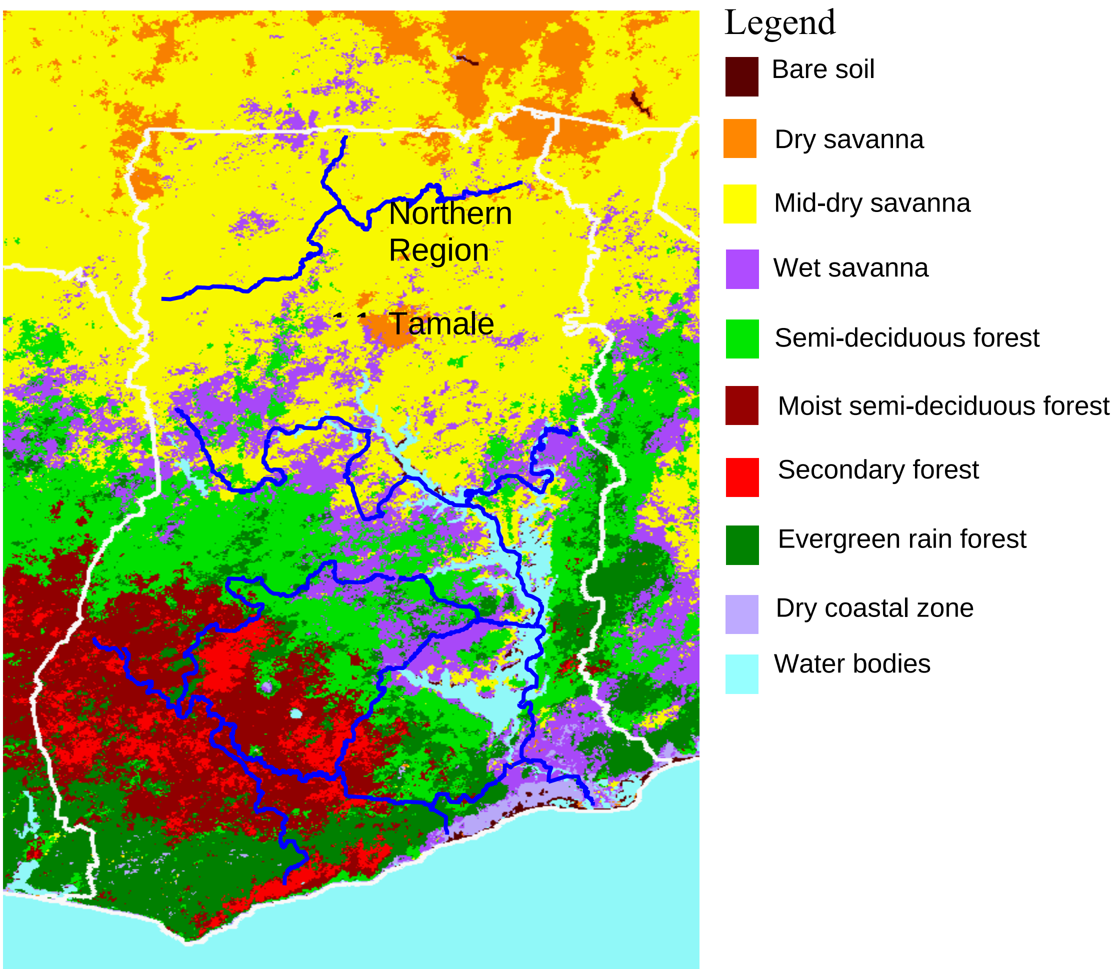


Figure 3.3: Vegetation map of Ghana (Menz and Bethke, (2000)

3.5 Land use

Subsistence agriculture is the main occupation of the people in the area. Farms are of two types: the compound farms, which lie immediately around the house, and the bush farms, which may border on the compound farm or be located several kilometres away from the main village. The crops in the area include okra, tobacco, gourd melon, tomato, black pepper, sweet potato, early and late millet, guinea corn, maize, cowpeas, bambarra beans, cassava and yam.

4 MATERIAL AND METHODS

4.1 Characterization of vegetation in the study area

Vegetation is usually defined as the mosaic of plant communities in the landscape. The vegetation cover as a measure of plant distribution is of great ecological significance. With regard to bushfires, the structure, composition and spatial distribution of the vegetation determine the type of fuel load or biomass, its arrangement and to a large extent its quantity and quality, as well as the amounts of nutrients volatilized or transferred as particulate material. This is important because the total transfer of carbon and most nutrients depend on the quality and quantity of the fuel load.

The description of the vegetation was carried out by adopting Dansereau's (1963) methodology for describing and recording vegetation on a structural basis. Structure is usually defined as the organization in space of the individuals composing a vegetation type or plant community. The term structural form often used hereafter will refer to the appropriate symbol of habit form in which the leaf shape and size, leaf texture, seasonality and coverage have been included. Structural comparison involves the actual spatial distribution of the habit form.

Westhoff (1967, 1968) observed that extreme habitat factors, like extreme temperatures or frequent burning, can lead to the phenomenon of floristically very similar but structurally quite different "twin formations". Overgrazing and trampling by domestic livestock often results in a reduction of the grass cover, soil erosion and bush encroachment. Furthermore, cutting of wood for fuel is a common practice in the study area. This leads to changes in species composition but also to a change in the vegetation structure and to the deterioration of the vegetation cover.

4.1.1 Site selection and description

A reconnaissance survey was carried out to assess the general vegetation structure of the study area. Forty-nine sites were sampled along major and minor roads in the study area. The sampling intervals were about 20 km along the major and minor roads, in the northern, southern, western and eastern directions of the study area using Tamale (regional capital) as the reference point.

All the sites (Tables 4.1a – 4.1f and 4.2a –4.2b) were a mixture of agriculture and fallow lands (4 - 20 years old). This information was obtained from informal interviews with the inhabitants close to the different sites; also, the conspicuous presence of ridges and mounds indicated recent cultivation. All the sites had experienced bushfires the previous year, which was evident from the black barks of the standing trees and shrubs and confirmed by nearby settlers.

Table 4.1a: Chemical properties of soils under different vegetation cover/structure at sample points in selected study sites

Number	**Site**	**Description**	**%N**	**%OC**	**%SOM**	**mg P g^{-1}**	**mg Ca g^{-1}**	**mg Mg g^{-1}**	**mg Na g^{-1}**	**mg K g^{-1}**	**CEC cmol$^{(+)}$ kg^{-1} soil**	**pH ($CaCl_2$)**
1	Sambu	Grass/herb with scattered trees and shrubs. Fallow period 5-7 years. Annual bushfires.	0.051	0.534	0.919	0.006	0.516	0.125	0.006	0.017	4.925	5.600
2	Salkpang	Grass/herb with scattered trees and shrubs. Fallow period 3 years. Annual bushfires.	0.059	0.271	0.466	0.001	0.693	0.214	0.006	0.020	6.793	5.530
3	Jimle	Open woodland savanna. Fallow period 10 or more years. Annual bush fires.	0.121	1.135	1.953	0.006	0.674	0.297	0.005	0.034	7.011	5.520
4	Juni	Widely open woodland savanna. Fallow period over 5 years. Annual bushfires.	0.048	0.606	1.043	0.007	0.206	0.177	0.011	0.017	4.977	4.930
5	Jaffour	Widely open woodland savanna. Fallow period not known (long). Annual bushfires.	0.104	0.959	1.649	0.008	0.796	0.177	0.014	0.027	8.060	5.640
6	Sabojida	Widely open woodland savanna. Fallow period not known (long). Annual bushfires.	0.053	0.405	0.696	0.009	0.071	0.084	0.003	0.015	3.801	4.590
7	Jagbojado	Open woodland savanna. Fallow period is about 5 years. Annual bushfires.	0.059	0.593	1.020	0.013	0.674	0.161	0.006	0.015	5.851	5.510
8	Nyamaliga	Grass/herb with scattered trees and shrubs. Fallow period not known. Annual bushfires.	0.061	0.564	0.970	0.003	0.564	0.217	0.006	0.022	6.083	5.310

Table 4.1b: Chemical properties of soils under different vegetation cover/structure at sample points in selected study sites

Number	Site	Description	%N	%OC	%SOM	mg P g^{-1}	mg Ca g^{-1}	mg Mg g^{-1}	mg Na g^{-1}	mg K g^{-1}	CEC $cmol^{(+)}$ kg^{-1} soil	pH ($CaCl_2$)
9	Gbung	Widely open savanna woodland. Fallow period not known. Annual bushfires.	0.058	0.431	0.741	0.007	0.629	0.214	0.011	0.022	6.705	5.420
10	Kpalbusi	Widely open savanna woodland. Fallow period at least 10 years. Annual bushfires.	0.079	0.895	1.539	0.023	0.880	0.207	0.006	0.039	8.123	5.510
11	Massaka	Widely open savanna woodland. Fallow period not known. Annual bushfires	0.051	0.615	1.058	0.004	0.113	0.116	0.005	0.008	3.158	4.810
12	Alhassan Kura	Savanna woodland. Fallow period not known but long. Annual bushfires.	0.054	0.648	1.114	0.012	0.170	0.150	0.007	0.014	3.350	5.550
13	Dagomba-Line	Savanna woodland, tree stratum dominates. Fallow period about 7 years. Annual bushfires.	0.053	0.489	0.841	0.009	0.473	0.114	0.003	0.016	3.956	5.820
14	Sarikyekura	Grass/herb with scattered trees and shrubs. Fallow period 5-7 years. Annual bushfires.	0.034	0.534	0.919	0.007	0.505	0.269	0.010	0.020	5.725	5.750
15	Ntreso	Open savanna woodland. Fallow period 3-5 years. Annual bushfires.	0.060	0.475	0.817	0.009	0.141	0.116	0.011	0.017	2.647	5.670
16	Jerimoape	Open savanna woodland. Fallow period not known. Annual bushfires	0.066	0.322	0.554	0.006	0.604	0.101	0.007	0.023	5.035	5.580

Table 4.1c: Chemical properties of soils under different vegetation cover/structure at sample points in selected study sites

Number	Site	Description	%N	%OC	%SOM	mg P g^{-1}	mg Ca g^{-1}	mg Mg g^{-1}	mg Na g^{-1}	mg K g^{-1}	CEC $cmol^{(+)}$ kg^{-1} soil	pH ($CaCl_2$)
17	Grupe	Widely open savanna woodland. Game reserve, no definite fallow period known. Annual bushfires.	0.053	0.385	0.662	0.004	0.743	0.158	0.006	0.021	5.685	5.700
18	Kanantu	Grass/herb with scattered trees and shrubs. No definite fallow period known. Annual bushfires.	0.048	0.830	1.427	0.010	0.736	0.185	0.014	0.021	6.706	5.550
19	Larabanga	Grass/herb with scattered trees and shrubs. Fallow period not known. Annual bushfires.	0.059	0.732	1.259	0.021	0.688	0.133	0.006	0.032	6.833	5.540
20	Damongo	Widely open savanna woodland. Fallow period about 5-10 years. Annual bushfires.	0.051	0.346	0.596	0.018	0.550	0.136	0.003	0.017	4.423	6.050
21	Joronkponto	Widely open savanna woodland. Fallow period 10 – 15 years. Annual bushfires.	0.142	0.648	1.114	0.020	0.552	0.168	0.006	0.027	4.732	6.020
22	Lansa-Kura	Grass/herb with scattered trees and shrubs. Fallow period at least 5 years. Annual bushfires	0.047	0.387	0.665	0.010	0.473	0.114	0.003	0.011	4.242	5.610
23	Gurugu	Open savanna woodland. Fallow period over 5 years. Annual bushfires.	0.033	0.447	0.768	0.019	0.061	0.064	0.008	0.013	2.195	3.390
24	Sinsina	Widely open savanna woodland. Fallow period about 5 years. Annual bushfires.	0.073	0.342	0.588	0.012	0.685	0.187	0.010	0.029	6.580	5.600
25	Jariguyili	Widely open savanna woodland. Fallow period bout 20 years. Annual bushfires.	0.045	0.376	0.647	0.006	0.057	0.055	0.003	0.012	4.178	4.120

Table 4.1d: Chemical properties of soils under different vegetation cover/structure at sample points in selected study sites

Number	Site	Description	%N	%OC	%SOM	mg P g^{-1}	mg Ca g^{-1}	mg Mg g^{-1}	mg Na g^{-1}	mg K g^{-1}	CEC $cmol^{(+)}$ kg^{-1} soil	pH ($CaCl_2$)
26	Nanton	Grass/herb with scattered trees and shrubs. Fallow period 3 years. Annual bushfires.	0.053	0.761	1.309	0.004	0.722	0.108	0.006	0.026	5.232	6.090
27	Zinindo	Widely open savanna woodland. Fallow period not known but long. Annual bushfires.	0.059	0.411	0.707	0.012	0.081	0.074	0.006	0.013	4.575	3.830
28	Gaa	Widely open savanna woodland. Fallow period about 5 years. Annual bushfires.	0.056	0.594	1.021	0.008	0.197	0.116	0.003	0.013	3.287	5.190
29	Kpandain	Grass/herb with scattered trees and shrubs. Fallow period about 5 years. Annual bushfires.	0.109	1.071	1.843	0.006	0.754	0.215	0.020	0.022	7.871	5.400
30	Nakoli	Grass/herb with scattered trees and shrubs. Fallow period not known but long. Annual bushfires.	0.147	0.978	1.682	0.007	0.833	0.307	0.017	0.044	10.073	5.290
31	Gbadori	Grass/herb with scattered trees and shrubs. Fallow period not known, but long. Annual bushfires.	0.058	0.870	1.496	0.009	0.097	0.185	0.005	0.011	4.851	4.550
32	Nasuan	Open savanna woodland, fallow period not known. Annual bushfires.	0.045	0.268	0.462	0.013	0.574	0.148	0.005	0.031	4.681	5.900
33	Gbambu	Open savanna woodland. Fallow period not known. Annual bushfires.	0.100	0.869	1.495	0.006	0.870	0.277	0.015	0.033	8.967	5.590

Table 4.1e: Chemical properties of soils under different vegetation cover/structure at sample points in selected study sites

Number	Site	Description	%N	%OC	%SOM	mg P g^{-1}	mg Ca g^{-1}	mg Mg g^{-1}	mg Na g^{-1}	mg K g^{-1}	CEC cmol$^{(+)}$ kg^{-1} soil	pH ($CaCl_2$)
34	Janga	Grass/herb with scattered trees and shrubs. No definite fallow period, quite long. Annual bushfires.	0.084	0.591	1.016	0.009	0.434	0.113	0.003	0.015	4.144	5.590
35	Kadia	Grass/herb with scattered trees and shrubs. Fallow period 3 – 5 years. Annual bushfires.	0.039	0.294	0.505	0.007	0.212	0.155	0.008	0.024	2.932	6.010
36	Kukobila	Widely open savanna woodland. No definite fallow period, but quite long. Annual bushfires.	0.058	0.638	1.097	0.007	0.086	0.174	0.006	0.019	6.284	4.080
37	Nabogu	Widely open savanna woodland. Fallow period over 10 years. Annual bushfires.	0.041	0.712	1.225	0.004	0.062	0.065	0.004	0.008	5.286	3.620
38	Loagri	Widely open savanna woodland. Fallow period not known. Annual bushfires.	0.078	0.643	1.105	0.012	0.539	0.165	0.004	0.027	5.231	5.730
39	Gbimsi	Widely open savanna woodland. Fallow period over 10 years. Annual bushfires.	0.054	0.643	1.105	0.009	0.702	0.118	0.004	0.024	5.157	5.930
40	Karimenga	Widely open savanna woodland. Fallow period not known but long. Annual bushfires	0.054	0.491	0.844	0.019	0.596	0.134	0.003	0.024	4.806	6.070
41	Timpella	Widely open savanna woodland. Fallow period about 3 years. Annual bushfires.	0.040	0.664	1.142	0.017	0.702	0.174	0.012	0.025	6.452	5.710

Table 4.1f: Chemical properties of soils under different vegetation cover/structure at sample points in selected study sites

Number	Site	Description	%N	%OC	%SOM	mg P g^{-1}	mg Ca g^{-1}	mg Mg g^{-1}	mg Na g^{-1}	mg K g^{-1}	CEC $cmol^{(+)}$ kg^{-1} soil	pH ($CaCl_2$)
42	Sadugu	Widely open savanna woodland. Fallow period over 5 years. Annual bushfires.	0.047	0.385	0.662	0.011	0.092	0.105	0.006	0.013	3.879	4.690
43	Daboyire	Widely open savanna woodland. No definite fallow period. Annual bushfires.	0.051	0.361	0.620	0.008	0.685	0.166	0.010	0.013	6.062	5.320
44	Bole-Bamboi road (60km)	Widely open savanna woodland. No definite fallow period, but quite long. Annual bushfires.	0.075	0.866	1.489	0.005	0.934	0.203	0.014	0.029	8.667	5.590
45	Lampoga	Tree savanna, herb stratum dominates. Fallow period 7-10 years. Annual bushfires.	0.033	0.583	1.003	0.008	0.123	0.138	0.006	0.011	2.807	5.380
46	Pishigu	Widely open savanna woodland. Fallow period 7 – 10 years. Annual bushfires.	0.056	0.651	1.119	0.009	0.587	0.122	0.006	0.024	5.221	5.450
47	Nyong	Open savanna woodland. Fallow period not known. Annually bushfires.	0.070	0.669	1.150	0.011	0.651	0.192	0.009	0.027	5.742	6.040
48	Tamaligu	Open savanna woodland. shrub stratum dominates. Fallow period not known. Annual bushfires.	0.045	0.351	0.604	0.011	0.094	0.201	0.006	0.013	5.386	3.940
49	Bontanga	Widely open savanna woodland. Fallow period not known. Annual bushfires.	0.043	0.324	0.557	0.011	0.531	0.311	0.012	0.015	5.895	5.870

Table 4.2a: Physical properties of soils under different vegetation cover/structure at sample points in selected study sites

Site	% Sand	% Silt	% Clay	Bulk density, g cm^{-3}
Sambu	48.9	45.8	5.3	1.3
Salkpang	57.9	35.8	6.3	1.4
Jimle	54.9	35.8	9.3	1.6
Juni	45.9	44.1	10.0	1.7
Jaffour	57.9	32.1	10.0	1.3
Sabojida	54.7	36.0	9.3	1.4
Jagbojado	43.9	48.1	8.0	1.4
Nyamaliga	46.7	47.0	6.3	1.4
Gbung	61.9	32.1	6.0	1.5
Kpalbusi	46.7	44.0	9.3	1.5
Massaka	64.7	30.0	5.3	1.5
Alhassan Kura	72.7	24.0	3.3	1.5
Dagomba Line	68.9	26.8	4.3	1.5
Sarikyekura	51.9	40.1	8.0	1.4
Ntreso	58.9	35.8	5.3	1.3
Jerimoape	55.9	40.2	4.0	1.4
Grupe	59.9	33.8	6.3	1.3
Kanantu	81.9	14.8	3.3	1.4
Larabanga	65.9	29.8	4.3	1.3
Damongo	80.7	14.0	5.3	1.4
Joronokponto	78.7	18.0	3.3	1.6
Lansa Kura	72.9	21.8	5.3	1.4
Gurugu	64.7	30.0	5.3	1.4
Sinsina	64.9	27.8	7.3	1.6
Jariguyili	54.9	36.8	8.3	1.5

Table 4.2b: Physical properties of soils under different vegetation cover/structure at sample points in selected study sites

Site	% Sand	% Silt	% Clay	Bulk density ,g cm^{-3}
Nanton	60.7	31.0	8.3	1.7
Zinindo	44.7	44.0	11.3	1.4
Gaa	44.9	47.8	7.3	1.4
Kpandain	58.7	36.0	5.3	1.7
Nakoli	44.7	48.0	7.3	1.4
Gbadori	57.9	34.1	8.0	1.3
Nasuan	81.9	16.1	2.0	1.5
Gbambu	59.9	36.1	4.0	1.4
Janga	56.9	33.8	9.3	1.4
Kadia	63.9	32.1	4.0	1.5
Kukobilla	56.7	34.0	9.3	1.5
Nabogu	56.7	34.0	9.3	1.5
Loagri	56.9	33.8	9.3	1.5
Gbimsi	65.9	28.8	5.3	1.5
Karimenga	72.9	21.8	5.3	1.4
Timpella	80.7	16.0	3.3	1.5
Sadugu	77.9	16.1	6.0	1.6
Daboyire	69.9	23.8	6.3	1.5
Bamboi road	63.9	30.1	6.0	1.2
Lampoaga	71.9	22.8	5.3	1.5
Pishigu	55.9	36.1	8.0	1.4
Nyong	61.9	28.1	10.0	1.5
Tamaligu	45.9	45.8	8.3	1.5
Bontanga	69.9	22.1	8.0	1.6

4.1.2 Vegetation description system based on Dansereau's diagrams

The structural system of Dansereau (1951, 1958), Dansereau et al. (1966), Dale (1979) and Kent and Coker (2001) was applied in this study to portray the vegetation cover types. Dansereau's system is based on plant structure and therefore largely applicable without knowledge of the taxonomic identity of the plants composing the vegetation, as this system provides assemblage of formulae and diagrams and more so relates to the quantity of fuel load expected. It is important to realize that in the present system, space relationships are emphasized, and major units are physiognomic rather than biological. The categories of criteria (Figure 4.1) were applied for the structural description of the vegetation of the selected sites. The codes associated with the symbols were used to describe the structure of each vegetation type/strata.

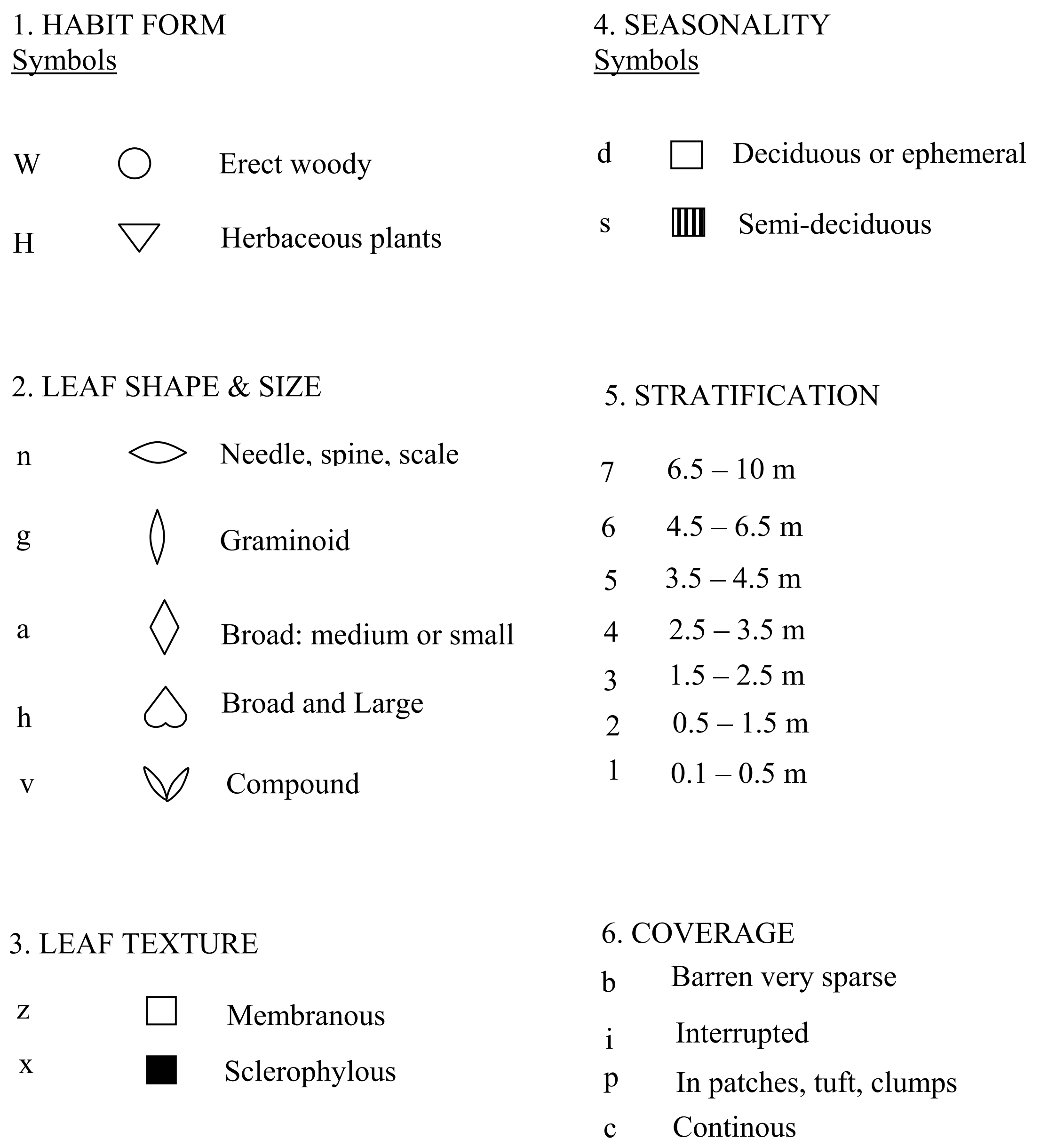


Figure 4.1: Scheme of six categories of criteria applied to the structural description of vegetation types (slightly modified from Dansereau, 1958)

4.1.3 Scale requirements

For the diagrammatic representation of physiognomic types, some scale requirements have to be met. The custom is to plot standard diagrams on squared paper where each square is 1cm x 1cm. A width of 25 squares allows coverage of 100 %, so that 1cm = 4% cover.

4.1.4 Field activity and data collection

One of the major objectives of the study was to adequately describe the vegetation in terms of the structure. Sampling started in August 2002 and an average of 10 –12 sites were sampled along each major road network at intervals of 20 km. In the cases where the 20 km mark fell on a settlement, the site was chosen just before or after that settlement.

At each site, informal interviews with settlers were carried out to obtain historical information about the area with regard to bushfires, land use and fallow periods. A representative transect of 4 m x 25 m was measured and pegged. All trees, shrubs, and herbaceous plants (grasses + legumes) were described using Dansereau's methodology. Their heights were measured. For trees diameter at breast height (dbh) was determined. Dominant species of trees, shrubs and herbaceous plants at each site were identified with the help of specialists from the Animal Research Institute (ARI) and Forestry Service, Ghana.

The coverage defined as the area of ground within a quadrant covered by above-ground parts of each species when viewed from above (Kent and Cooker 2001) was estimated separately for trees, shrubs and herbaceous plants. Soil samples and global positioning system (GPS) points were taken from the middle of the transect. Samples of soil were taken with an auger from 0-10 cm depth. Additionally, samples were taking using 100 cm^3 sampling rings for bulk density determination. All the 49 sites sampled were visited again in March 2003 to record any changes.

4.1.5 Description of land use and land cover based on satellite imagery

A cloud-free Landsat satellite image (7/11/1999, 194/52-53-54) of the study area was used to broadly classify the land use and land cover types. Geometric and radiometric rectification was done on the image and subsequently georeferenced and geocoded. A representative portion of the image was resized for further classification.

The spectral band combination for displaying images often varies with different applications (Trotter, 1998). This is important for the selection of training data for the subsequent classification. A band combination of red, blue and green (RGB) is often used to display images in standard colour composites for mapping (Trotter, 1998). In the current study, the Landsat TM image was displayed in a band combination of 4, 3 and 2 (red, blue and green), which is standard for visual interpretation of vegetation mapping in the tropics (Prakash and Gupta, 1998; Trotter, 1998). With this band combination (Figure 4.2), vegetation areas appeared in shades of red and sparsely vegetated areas in faint red (X); water bodies and burnt areas appeared black (Y); roads (not tarred), bare land and wastelands appeared in shades of dirty white and grey (Z), and settlements appeared in shades of grey, bluish-grey, steel grey, (Q) (Prakash and Gupta, 1998).

Field reconnaissance visits were carried out in order to be sure of accurate image classification. Effective interpretation of the image using supervised procedures requires a prior knowledge of the scene (Sunar, 1998). This information was obtained from ground-truth data and GPS points. Training pixels were selected on the 1999 image and located on the field. The reconnaissance survey provided first-hand information, the acquisition of accurate locational data and the interviewing of farmers, local settlers and experts as is recommended by Campbell and Browder (1995).

The image was digitally classified using the ENVI 3.5 program because digital (spectrally-oriented) classification is commonly used and has been found to give better results for vegetation mapping than visual classification (Bottomley, 1999). Supervised classification was employed in this study and involved three major steps: (1) selection of training pixels, (2) evaluation of training signature statistics and spectral pattern and (3) classification of the images (Lillesand and Kiefer, 1994; Trotter, 1998). The maximum likelihood algorithm was selected for the supervised classification of image data and offers the best results (Bresci, 1992; Stemmler and Su, 1993).

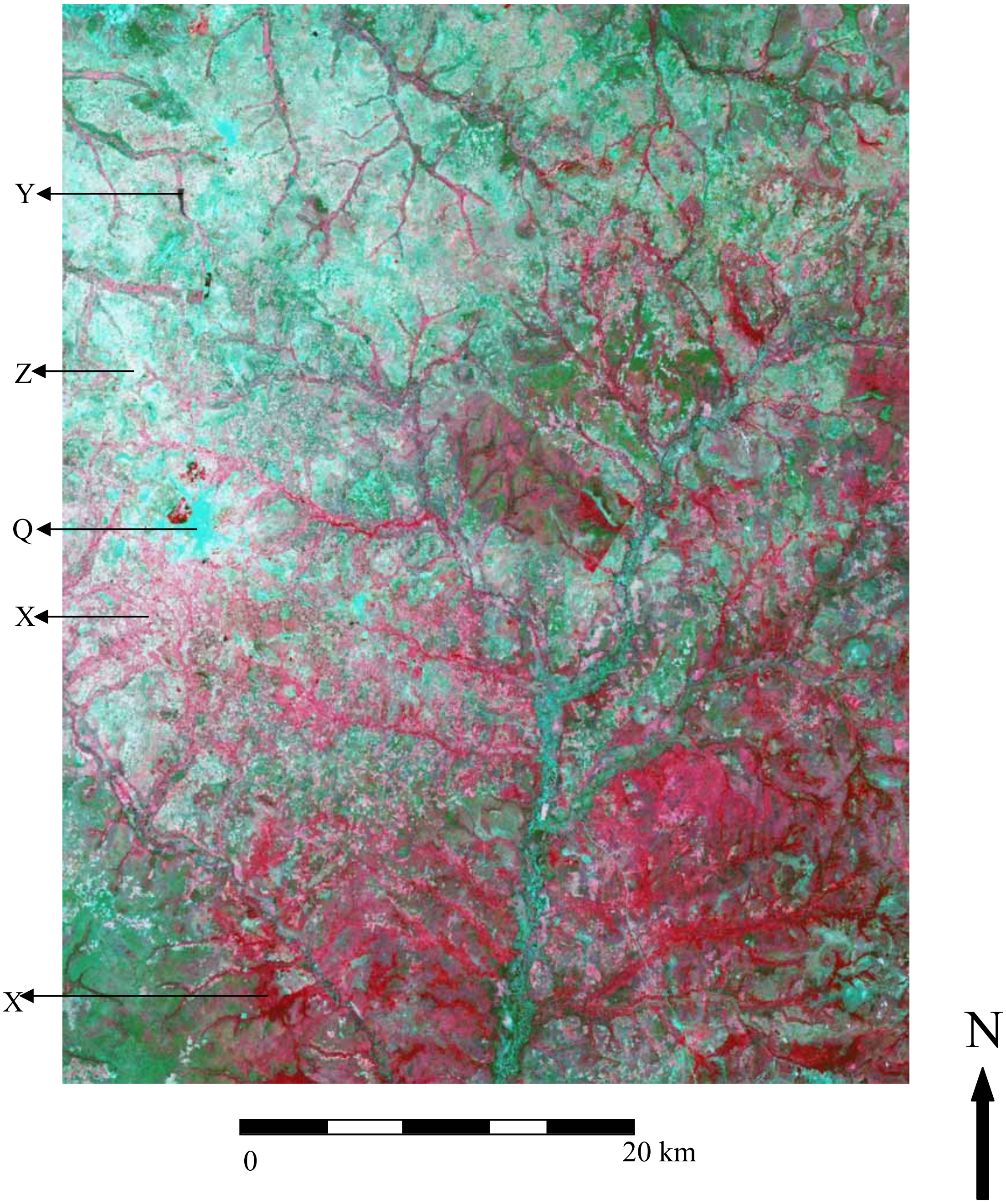


Figure 4.2: Landsat 7 ETM + image displayed in 4, 3, 2 (RGB) band combination, 7/11/ 1999

X=Vegetated areas in shades of red and sparsely vegetated in faint red
Y = Water bodis and burnt areas appear black
Z= Roads, bare land and wastelands in shades of dirty white and grey
Q= Settlements in shades of grey, bluish-grey and steel grey

4.2 Fuel load estimation and bushfire experiment

4.2.1 Site selection and description

Five vegetation cover types representative of the study area were selected for the fuel load estimation and bushfire experiment in five different sites (Figure 4.3). These vegetation cover types are: Tree savanna, shrub savanna, grass savanna, grass/shrub savanna and grass/tree savanna. These vegetation cover types account for the heterogeneity of the general vegetation cover of the study area.

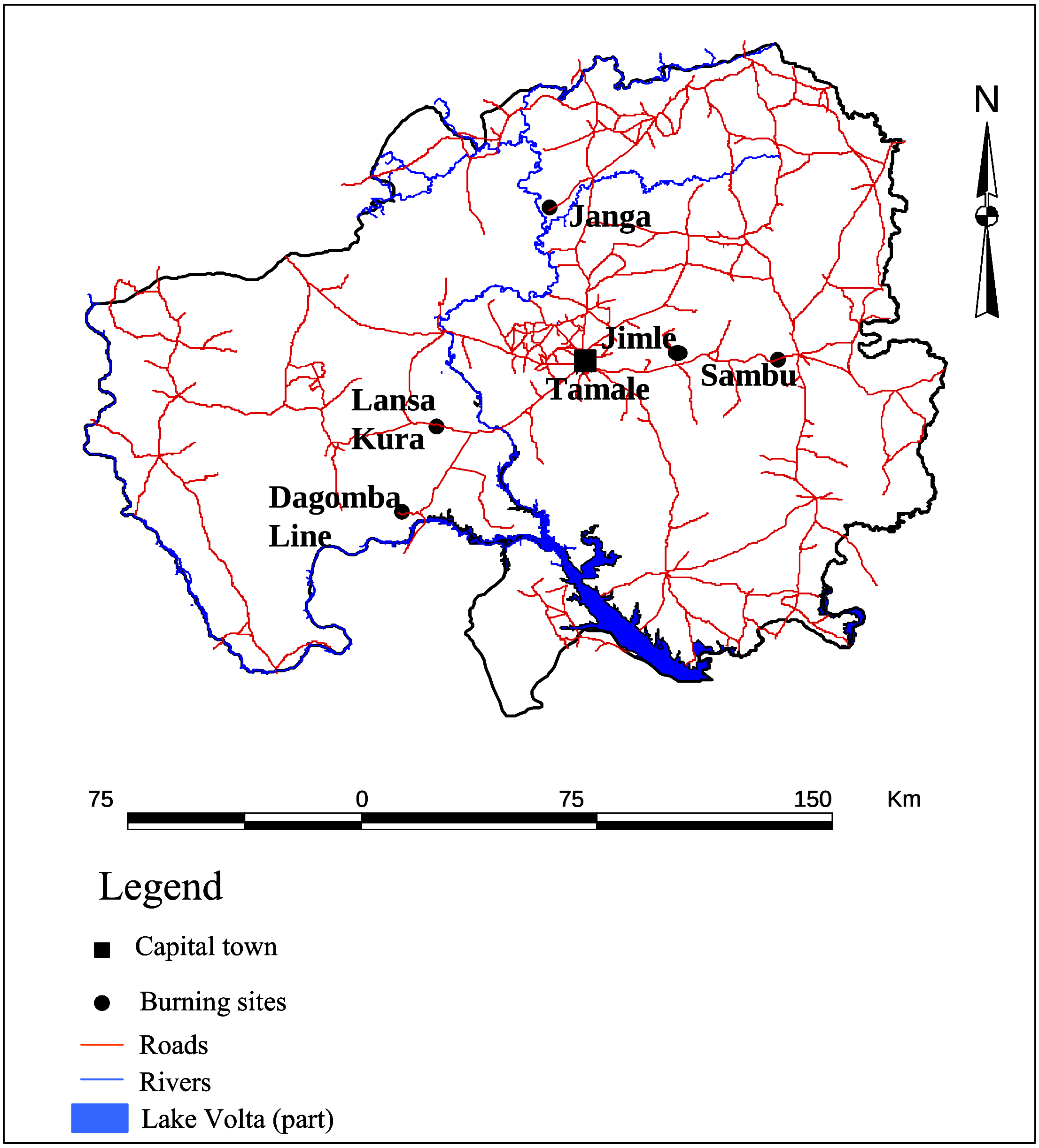


Figure 4.3: Locations of the experimental bushfire sites

Tree savanna (TS) has a dominant tree component with a density > 150 trees ha^{-1}. The closed savanna woodland is mostly restricted to reserved lands. However, some of these woodlands have been intensively degraded because of the higher population densities in these areas. Population growth contributes to the degradation of woodlands because of the increased clearing of land for farming and exploitation of wood for construction and fuel wood. Other land use includes conservation or traditional grove, open access woodland that may contain scattered farms. The selected location for experiment had a long fallow period and experience bushfires annually.

The shrub savanna (SS) is dominated by the shrub component. It is found mostly in areas that have been farmed for a very long time and where the economic trees have been left on the land. It is also found in areas that, though not cultivated, could not develop tree vegetation due to various edaphic factors. Permanent fallow is the dominant land use type. However, long fallow cropping system and mixed bush fallow cropping system land use types are present, in this particular location the fallow period was more than 10 years and experiences annual bushfires.

In the grass savanna (GS), the most dominant component is grass with a tree density < 10 trees ha^{-1}. This has developed as a result of human intervention by the clearing of the vegetation cover for cultivation and left to fallow. It is always found in association with farmlands. Short fallow, mixed bush fallow cropping systems are common. The selected location for the experiment was a bush fallow with fallow period of 4 years, fallows are burnt annually.

Grass/shrub savanna (GSS) has a vegetation cover type characterized by shrub and tree components which are widely scattered and interrupted with grass coverage. It has developed through the continuous and intensive exploitation of the open savanna woodland for timber or fuel wood, other products and incessant fire as well as for agricultural purposes. This is the most common or expansive vegetation type in the study area and found almost everywhere. Permanent fallow dominates, however long fallow and mixed bush fallow cropping systems are present. Site for the experiment is a permanent fallow land use type and experience annual bushfires.

Grass/tree savanna (GTS) is dominated by grass component with tree density higher than that of GS (> 10 trees ha^{-1}). This has developed as a result of human intervention by the clearing of the closed and open savanna woodland areas for cultivation and left to fallow. It is always found in association with farmlands. Short and long fallow, mixed bush fallow cropping system. The selected location had at least 5 years fallow and burnt during the dry season.

Since these sites were to be protected for the fire experiment, permission had to be sought from local chiefs, assemblymen of the areas, Rural Fire Department of the Ghana National Fire Service, Environmental Protection Agency (EPA) and finally the Ministry of Food and Agriculture (MOFA).

4.2.2 Layout of field experiments

In October 2002, a representative area of 50 m x 100 m was demarcated for each of the five sites mentioned above, pegged and fenced with a barbed wire and a signboard erected (Figure 4.4).

Figure 4.4: Experimental bushfire site at Janga, during fire

Within the fenced area, 20 main plots of 10 m x 10 m were marked and pegged at each site (Figure 4.5). Adjacent to each main plot, a sub-plot of 5 m x 5 m was set aside for vegetative matter (fuel load) sampling. The 10 m x 10 m plots were left undisturbed for the control burning to simulate field conditions, which is the nature of occurrence of bushfires in this area.

At each site a 10 m wide fire belt was created around the demarcated area and a caretaker was hired to look after the place.

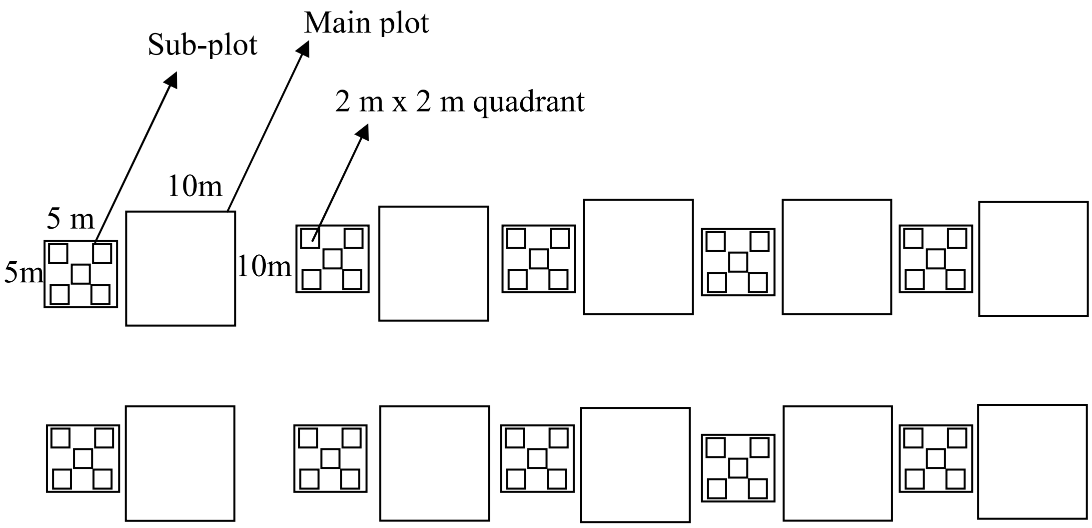


Figure 4.5: Schematic diagram showing experimental plots

The fire belt was created by weeding and removing all debris to expose the bare ground to prevent the area from getting burnt accidentally especially as the dry season was approaching. The sites were visited regularly to ascertain the situation on the ground.

4.3 Fuel load sampling

Fuel load for the purpose of this study is defined as all combustible aboveground vegetative matter (excluding the stems of standing shrubs and trees). This included dead and fallen leaves, fruits and seeds from trees and grass, herbs, standing grass, downed woody debris or twigs, and attached foliage on small trees and shrubs. The material was sorted into herbaceous plants (mainly grasses), leaves, twigs and litter components. It is important to note that after intense bushfires, the trees and shrubs with black, burnt bark are left standing in the study area; for this reason they were not included in the fuel load assessment or the combustible materials.

Fuel load sampling was carried out in two phases in December 2002 in the first 10 sub-plots, and in February 2003 in the other 10 sub-plots. Five 2 m x 2 m random quadrates were taken from the sub-plots of 5 m x 5 m for fuel load sampling.

All the combustible vegetative matter was cut to ground level with a sickle and separated into herbaceous plants (mainly grasses), leaves and twigs for November/December sampling and into herbaceous plants (mainly grasses), litter and twigs for January/February sampling. The difference in fuel load components is due to the fact that during January sampling it was difficult to actually pick the leaves separately. The leaves were so dry and had broken into pieces and a few herbaceous plants (mainly grasses) had also broken, thus producing a mixture on the ground.

The samples were weighed in the field with a Salter model 250 scale and later reduced to 500 g per sample and oven dried at 75^{o}C for 48 hours at the Savanna Agriculture Research Institute (SARI). Dried samples were weighed for dry matter conversion and later ground for chemical analysis of carbon (C), nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) content.

4.4 Bushfire experiment

Just as for the fuel load sampling, the burning was carried out in two phases. The first phase was in early December 2002, and the second in early February 2003. Through informal interviews with farmers and settlers in the burning sites, two bushfire periods were identified as December (early dry season bushfires) and February (late dry season bushfires).

In order to assess the carbon and nutrient stocks left after burning, it was necessary to collect ashes immediately after burning. Fifty ash trays of size 0.5 m x 0.5 m and height 2 cm with lids were locally constructed from iron sheets to collect ash and fragments deposited during the fires. Prior to burning, 5 trays were randomly placed on each of the 10 m x 10 m plots; the fuel load was removed to place the trays on the soil surface and replaced on top of each tray (Cook, 1994).

Herders and local farmers were asked to start the fire. For this they used a torch of dried grass lit with a match and introduced it in the field on one side in the direction of the wind (head-fire). The duration of the burn was determined. A Casella wind vane was used to record the speed and direction of wind, before, during and immediately after burning. An infrared thermometer with laser marker (Thermomega OS643E-LS) was used to measure the temperature of the flames from bottom to top.

Immediately after the burning, the ash trays were covered with the lids to avoid the ash being blown off by wind. The trays were left on the field overnight to cool and the ash collected into envelopes early in the morning when the wind speed was relatively lower. The total ash collected from each tray was weighed at SARI using a sensitive weighing scale and later separated into < 1mm and > 1mm fractions and weighed again. These fractions are referred to as fine and coarse ash, respectively. The coarse ash was ground and bulked samples of each fraction from each main plot (10 m x 10 m) used for analyses of carbon and nutrients content at the SARI soil and plant analyses laboratory.

The carbon and nutrient stocks were calculated for each main plot by multiplying the mean fuel load dry matter by the carbon and nutrient concentrations obtained from the chemical analyses. The transfer of carbon and nutrients to the atmosphere was calculated as the difference between the mean carbon and nutrient stock of the fuel load and that of the ash.

4.5 Albedo measurement

Albedo (α) is the fraction of light that is reflected by a body or surface or short wave reflection coefficient of a surface. It can be defined as

$$\alpha = \frac{K\uparrow}{K\downarrow} \qquad (1)$$

where $K\uparrow$ and $K\downarrow$ are reflected and incoming hemispherical radiances, respectively.

Measurements of incoming and reflected radiances were taken from burnt and unburnt plots of different vegetation cover types (grass savanna, shrub savanna, grass/shrub savanna, grass/tree savanna and tree/savanna) in the study area using a pyranometer (model: SP LITE, Kipp and Zonen, Table 4.3) positioned upright and inverted directly over the surfaces. The albedo was calculated from the above expression. The response of the pyranometer is less than one second. Twenty-five readings of incoming and reflected radiances were taken. Surface temperature was taken with an infrared thermometer (Thermomega OS643E-LS); the soil moisture content and color of ash was also recorded. The measurements were taken from 05/02/2003 to 13/02/2003, between 1200 noon and 1330 hours GMT. At each site, albedo and soil surface temperature measurements were taken from 5 unburnt and burnt plots.

Table 4.3: Sensor type, properties and specifications

Specifications	Pyranometer type SP LITE
Field view	180^0
Response time	<1 sec
Sensitivity (calibrated)	77.06μV/W/m^3
Tilt response	No error
Non-linearity	<± 1%
Non-signal range	0-0.2V
Spectral range	0.4- 1.1μm
Operating temperature	-30 - +70
Sensitivity to temperature	0.15%/^{0}C

4.6 Modeling surface energy budget and moisture indicators with BATS

The model adopted in this exercise for simulating surface energy fluxes and moisture indicators is the Biosphere-Atmosphere-Transfer Scheme (BATS). It has been developed as a comprehensive one-dimensional (1D) model for studying land-surface processes. The motivation behind the development of BATS is to (a) determine the fraction of incident solar radiation that is absorbed by different surfaces and the net radiation exchange of thermal infrared radiation, (b) calculate the transfers of momentum, sensible heat, and moisture between the earth's surface and atmospheric layers, (c) determine values for wind, moisture, and temperature in the atmosphere, within vegetation canopies, and at the level of surface observations, and (d) to determine (over land) values of temperature and moisture quantities on the earth's surface.

A review of the key model physics of the BATS scheme relevant to this study can be found in Dickinson (1991); Dickinson et al., 1991); Dickinson and Kennedy (1991and 1992); and Mearns et al. (1990).

Model initialization and parameter specifications

The BATS scheme was applied in this study and initialized with configuration and observation data. The model setup closely follows the test case given in the BATS 1e version (http://www.atmo.arizona.edu/cgi-bin/batsreadme.pl), but customized with initial and boundary conditions obtained from the measurement campaign in this study at the 5 experimental sites with different vegetation cover types. Parameters that could not be measured were taken from equivalent (default) land use data in the BATS scheme and other literature (Chen and Dudhia, 2001) with conditions similar to the region. These model calculations consist of diurnal integration for 5 different vegetation cover types representing the 5 experimental sites. The scheme was configured with 3 soil layers. The time step for the model simulations was 30 minutes. The BATS land surface scheme computes surface energy fluxes based on the input data and model configuration data. In particular, the weather data (Table 4.4), albedo measurements and the soil and vegetation parameters (Table 4.5) specific to the savanna conditions in the BATS were used to simulate the energy fluxes, moisture indicators and other state variables.

Initial soil moisture plays a critical role in partitioning the available energy between sensible and latent heat fluxes. Since the investigation was performed under harmattan conditions, the initial soil moisture was very critical in regulating the partitioning of the surface fluxes. Additionally, since the prevailing atmospheric humidity is very low, the only means of moisture transport was from the soil moisture intake by the roots of the semi-deciduous plants of the mosaic savanna vegetation. Particularly for the burnt case, there was no opportunity for soil moisture transport into the atmosphere, so that evapotranspiration was zero apart from the early morning dew that was deposited on the land surface. Care was taken to ensure that the model was producing the correct results by constraining the model with prior information. Because of the complex climatic conditions of the harmattan, the moisture indicators were restricted to the time between 0600 to 1800 GMT to ensure they were within realistic bounds.

The atmospheric data used for driving the model were the monthly mean values obtained from the meteorological office. The model was not forced with observations since such data were not available. This did not significantly affect the accuracy of the results, because the experiment was performed for a short duration such that the soil moisture depletion would remain constant over the simulation period. More importantly, as the climatic conditions were fairly constant during the duration of the experiment there were no significant errors in the model results. Deep soil temperature and moisture content measurements were not available, hence values based on local knowledge and experience from other measurements were used. The above assumptions offer realistic initial and boundary conditions for driving the simulations.

The simulation was performed for both the burnt and unburnt savanna, where the unburnt savanna served as the control experiment. The experiment was repeated for the 5 experimental sites with initialization data obtained at each site.

The control experiment is characterized by mosaic savanna land use. The soil physical properties are the natural soil of the region of the soil type "class II" characterized following Cosby et al. (1984). The soil physical properties are given in Table 4.5. The control experiment was undertaken to stimulate the observed state variables as close as possible because observations were not available. It was based on the unburnt savanna, which is the natural vegetation for the area under investigation, and was used as a guide for determining how much the bushfire changes the default/original energy fluxes and moisture indicators.

For the burnt case, the harmattan climatic conditions coupled with the state of the soil result in desert-like behavior. Hence data in desert or semi-arid conditions are applicable when combined with the appropriate local knowledge of the experimental site.

The simulation was performed for burnt and unburnt savanna. For the burnt savanna, parameter values for post-bushfire were used as initial and boundary conditions for driving the model. In this case, drastic changes in albedo values were observed (see Table 5.24). The nature and extent of burning determine to a larger extent the albedo values. Additionally, the soil hydraulic properties were not significantly different (within the limit of experimental errors) from the unburnt, since only the uppermost layer, which constitutes a narrow depth of the vertical soil profile, was affected by the burning. However, the metric potential was significantly affected since observable differences exist between the burnt and unburnt cases.

Table 4.4: General weather conditions during dry season burning from the study sites in northern Ghana as measured on the day of ignition (February 2003)

Vegetation cover type	Shrub savanna	Grass savanna	Grass/shrub savanna	Grass/tree savanna	Tree savanna
Date (day/month/year) and time of fire	5/2/2003 13: 30	4/2/2003 13: 20	7/2/2003 13: 00	9/2/2003 13: 05	13/2/2003 13: 00
Duration of fire (minutes)	5	3	7	4	10
Wind direction	S	W	W	E	E
Wind speed (m s^{-1})	4. 5	5. 0	2. 5	4.0	2. 7

Table 4.5: Soil and vegetation parameters of the savanna used in the BATS Model. Soil and vegetation parameters for the unburnt conditions are based on the BATS code specific to the savanna environment (Dickinson et al., 1993) and on data collected in this study. Burnt soil parameters calculated using regression equations of Raw et al., 1982

Parameter	Value	
	Unburnt	Burnt
Soil parameters		
Soil type	2	2
Index for soil color	5	8
Soil wetness factor	0.02	0.002
Saturation soil suction Ψ_{sat} (m)	0.030	0.030
Clapp and Hornberger (1978), b	4.0	4.0
Saturated hydraulic conductivity, K_{sat} (m s^{-1})	8.00E-5	8.05E-5
Volmetric water content at saturation, θs m^3 m^{-3})	0.30	0.36
Wilting point, θ_w (m^3 m^{-3})	0.119	0.119
Field capacity, θ_{fc} (m^3 m^{-3})	0.477	0.477
Vegetation parameters		
Vegetation fraction, σ_f	0.3	0.0
Vegetation type	17	8
Roughness length, Z_0 (m)	0.1	0.005
LAI min	0.5	0
LAI max	6	0
Minimum stomatal resistance, Rcmin (s m^{-1})	200	999.9

4.7 Remote sensing of burnt areas

Fires in ecosystems are often very large and difficult to access for comprehensive field studies. Satellite remote sensing systems are, therefore, used to overcome this difficulty. By virtue of the frequently, wide area coverage provided by earth-orbiting platforms, satellite remote sensing can provide detailed information on location, frequency and spatial distribution of vegetation fires, data that is unavailable using other methods of investigation. In this study, the Landsat 7 ETM+ system was used.

4.7.1 Brief characteristics of Landsat 7 ETM+ system

Landsat 7 was launched in April 1999 and is currently the most modern platform of the Landsat program that started in 1972. It carries the "Enhanced Thematic Mapper Plus" (ETM+) sensor, a passive, optical across-track-scanner, which records the reflected portion of the electromagnetic radiation and the Earth's emitted radiation in the thermal band. With an inclination to the equator of 98.2° and an equatorial crossing time at 10:00 am +/-15 min (descending node), Landsat 7 belongs to the near-polar, sun-synchronous orbiters. Orbiting at an altitude of 705 km, it has a period of revolution of 99 minutes and covers an area every 16 days.

The design of the ETM+ stresses the provision of data continuity with other Landsat systems. Similar orbits and repeat patterns are used, as is the 185-km swath width for imaging. The system is designed to collect 15-m-resolution “panchromatic” data and six bands of data in the visible, near-IR, and mid-IR spectral regions at a resolution of 30 m (Table 4.6). An eight thermal band is incorporated with a resolution of 60 m (vs. 120 m for the ETM). The Landsat ETM system is indexed with path and row numbers according to the Worldwide Reference System (WRS), the scenes and consequently the areas they cover are uniquely identifiable.

The vast part of the study area is covered by the image strip consisting rows of 053 and 054 in path 194, while taking in to account the overlap between neighbouring paths. The scenes mainly used in this study were captured on 14 March 2000 (194/053-054).

Table 4.6: Spectral and spatial resolution of Landsat 7 ETM+, adapted from: Lillesand and Kiefer 2000

Band	Sensitivity (µm)	Spatial Resolution (m)
1	0.45-0.52	30
2	0.52-0.60	30
3	0.63-0.69	30
4	0.76-0.90	30
5	1.55-175	30
6 (thermal)	10.4-12.5	60
7	2.08-2.35	30
8 (panchromatic)	0.50-.090	15

4.7.2 Image selection and analysis

For the study area, an entirely cloud-free Landsat 7 ETM+ image was purchased at level 9 processing with systematic radiometric and geometric corrections applied to the data. Input images were rectified and registered to the 1: 50 000 topographic maps of the study area, which were the largest available. Following the correction, resampling was performed using the nearest-neighbor algorithm to ensure that the geometric integrity of the data was maintained. The final georeferenced and corrected image indicated that registration errors were very small.

Two aspects of post-fire landscapes are responsible for the spectral characteristics of burnt areas: the deposition of charcoal and ash as the direct result of burning, and the removal of photosynthetically active vegetation (Robinson, 1991). The spectral difference between burnt and unburnt savanna vegetation is most distinct in the near- and mid-infrared, where reflectance of a burnt area is low compared with the surrounding unburnt vegetation (Pereira and Setzer, 1993). The Landsat imagery used for mapping out burnt scars has seven bands, and this is significant because of the availability of two mid-infrared bands (bands 5 and 7) that have been shown to be particularly appropriate for distinguishing between burn and unburn vegetation (Eva and Lambin, 1998; Koutsias and Karteris, 2000).

The automated fire-scar mapping methodology was used to distinguish burnt scars and active fire. Manually defined samples of pixels from homogenous areas that were known to have burnt or to have remained unburnt were selected from a false color composite made-up of different band combinations: 3, 4, 5; 5, 4, 3 and 7, 5, 4. The 3, 4, 5 (RGB) band combination (Figure 4.6) and 7, 5, 4 (RGB) band combination (Figure 4.10) were used for selecting training areas for classification of burnt areas. These training areas were then used to automatically define fire-scars on the image using a maximum likelihood decision rule in supervised classification (Schowengerdt, 1983).

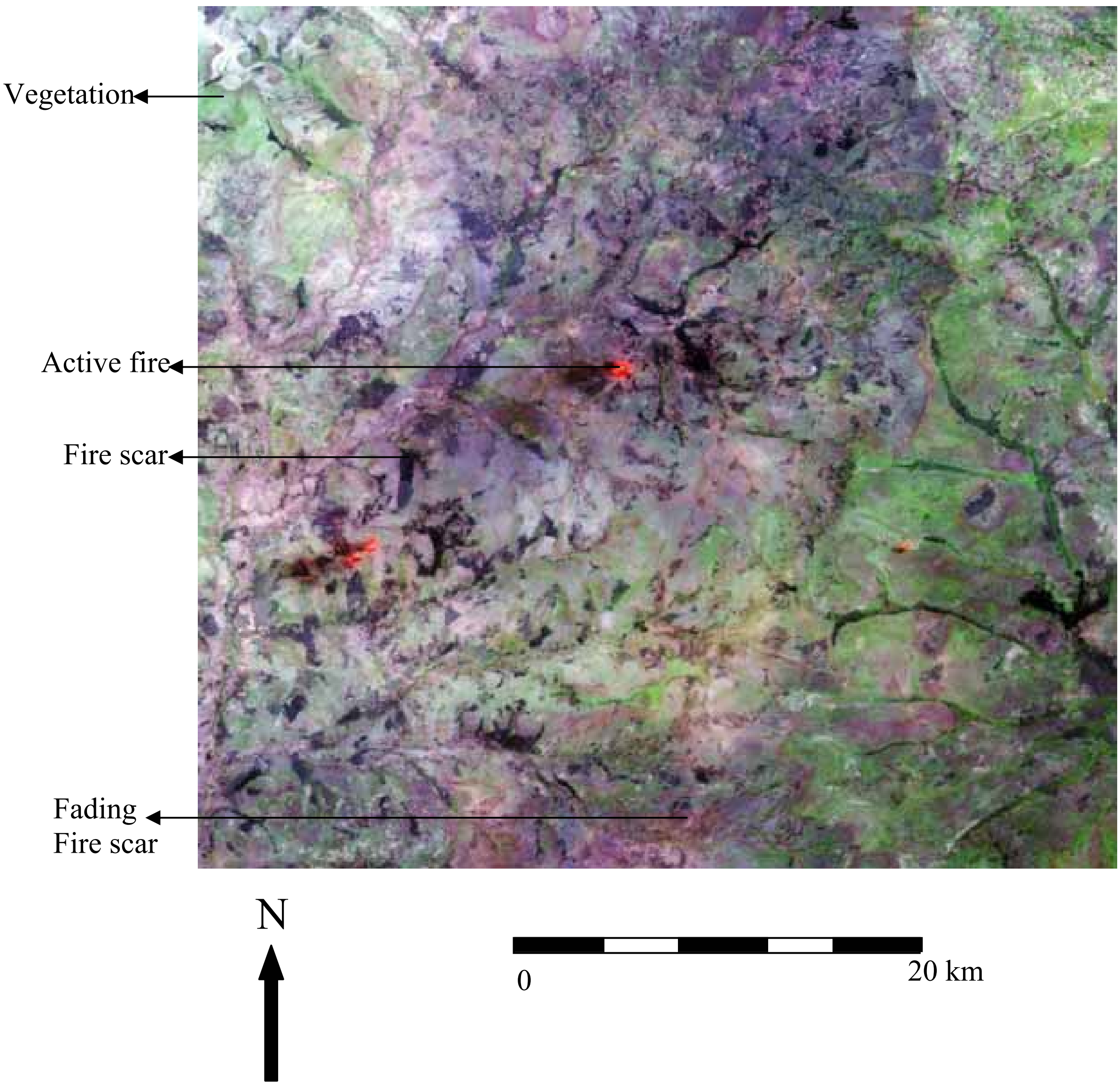


Figure 4.6: Landsat 7 ETM + image displayed in 5, 4, 3 (RGB) band combinations, 14/03/2000

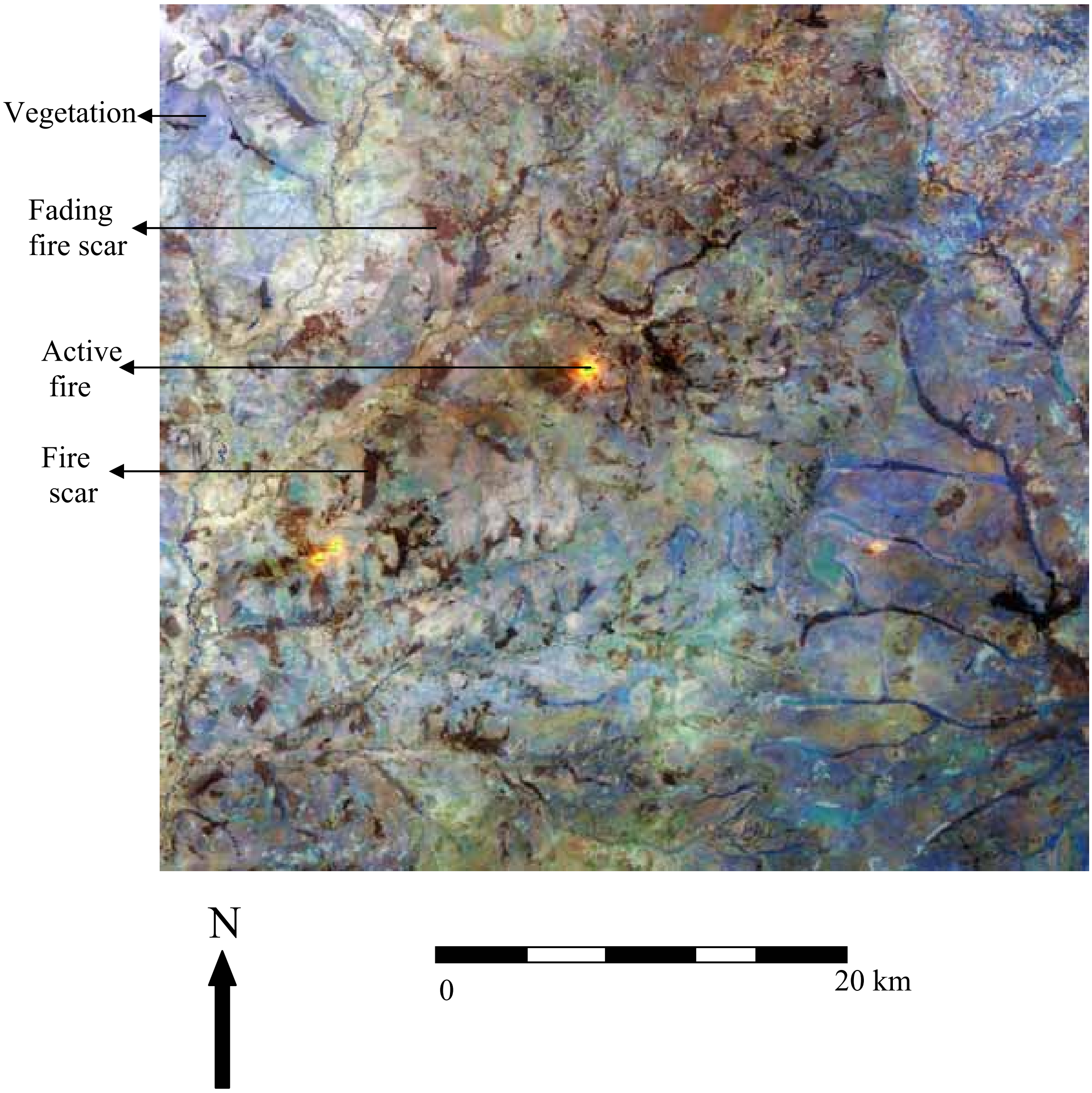


Figure 4.7: Landsat 7 ETM + image displayed in 7, 5, 4 (RGB) band combinations, 14/03/2000

In the 3, 4, 5 (RGB) band combination, active fire appears as red, fire scar appears as black, faded fire scar is in shades of brown, and vegetation appears in shades of green (Figure 4.6), while in the 7, 5, 4 (RGB) band combination active fire is yellow, fire scar appears in black and dark brown, and faded fire scar appears in brown shades (Figure 4.7).

An area of 20 km x 20 km of each experimental site was classified and the burnt area estimated for the subsequent calculation of carbon emissions from these sites. Even though a historic image was used, ground-truth information from interviews from key informants who identify themselves as hunters, herders, or farmers were used to adequately classify the image. Transect walks with local experts to identify and map burn scars and soil/vegetation patterns were also carried out.

4.8 Chemical analyses

4.8.1 Plant sample analyses

The concentration of carbon and nutrients in the plant samples was determined at the SARI soil and plant analyses laboratory. The plant samples were finely ground to pass through a 1mm mesh sieve. Bulked representative samples of herbaceous plants (grass), leaves, litter, twigs and ash were used for the analyses.

Using the standard methods of IITA (1979), C, N, P, K, Mg, Na, and Ca were analysed. Total N was determined by the Kjeldahl procedure. For P, K, Mg, Na, and Ca, the plant material was digested in H_2SO_4. The P content of the digest was analysed calorimetrically by the Vanado-Molybdate method. Ca and Mg were measured using the atomic absorption spectroscopy (AAS), Perkin-Elmer model 1000, whereas K and Na were measured by flame photometry. Total C was analyzed by the induction furnace method (Perkin-Elmer 2400 elemental analyzer).

4.8.2 Soil sample analyses

Soil samples were air-dried and passed through a 2 mm sieve and subsequently analyzed in the laboratory for pH (1: 2.5 $CaCl_2$), organic carbon (Walkley-Black), available P (Bray-P), and total N (Kjeldahl). Exchangeable bases (1N NH_4-acetate) and CEC were calculated by summation of the alkaline metal cations, alkaline-earth metals cations (Ca, Mg, K, and Na) and the acidic cations (H^+ and Al^{3+}) by converting them to $cmol^{(+)}$ per kg soil. Particle size distribution was measured using the hydrometer method (Bouyoucos, 1962), whereas core-sampling method was used to measure bulk density.

4.9 Statistical analyses and software applied

Data were statistically analyzed using the SPSS 11.0 and S-PLUS 6 statistical packages. ANOVA with site as a factor was calculated for fuel load and carbon and nutrient using the General Linear Model procedure of the software SPSS 11.0. If the overall F-test was significant, differences among the means were tested by Bonferroni test with a significance level of $P< 0.05$. The software package S-PLUS 6 was used to perform paired *t-tests* between burnt and unburnt sites and also for comparison between the two periods (December 2002 and February 2003). Cluster analyses was used to group different vegetation cover types. Satellite image classification was done using the software ENVI 3.5.

5 RESULTS AND DISCUSSION

5.1 Soil characteristics of study area

The results of the analysis of bulk soil samples taken from the study area are shown in Table 5.1. The soil texture of the area is characterized by sandy top soil with relatively low clay content and the textural class sandy loam (Landon, 1991). The dominant sand and silt fractions of the soil are a result of deposits from the harmattan winds (Dawidson and Nilsson, 2000). The bulk density is consistent with results obtained elsewhere in the study area (Fugger, 1999).

Low CEC values of 5.4 ($cmol^{+}$ kg^{-1}) are observed. This is attributed to the low soil organic matter (SOM) content and kaolinitic clay minerals. Exchangeable cation (K, Ca, Mg and Na) values were rated at reaching the critical range or above it (Landon, 1991), with Ca and Mg as dominant exchangeable cations. Similar results have been reported by Fugger (1999) from northern Ghana.

The soils are moderately acidic with very low organic carbon (OC) and total nitrogen (OC < 1 %, total N < 0.1 %). Low organic matter is closely related to availability of nutrients in the soil for two important reasons (Nye and Stephens, 1962): firstly, it contributes significantly to the high CEC of 150-200 ($cmol^{+}$ kg^{-1}) compared to the 9 $cmol^{+}$ kg^{-1} of the clay; secondly, the total soil nitrogen reserve and a substantial part of the phosphorus is associated with organic matter. Thus, the soil fertility of the study area is synonymous with SOM. Though the decomposition rate is relatively lower in the savanna compared to the forest agroecological zone, the supply of fresh materials is markedly reduced by annual bushfires (Greenland and Nye, 1959). The soils reported in this study have been rated as P deficient (Landon, 1991; also Fugger, 1999). Abekoe and Tiessen (1998) report that soils from semi-arid northern Ghana are inherently low in plant available P, its sorption and mobility. The results of the soil nutrients are within the range of values obtained in a recent characterization of soils of northern Ghana (SRI, 2001).

Table 5.1: Selected soil chemical and physical properties of the study area in the savanna of northern Ghana (August 2002, soil depth 0 –10 cm)

Soil parameter	Mean	Standard Error	Minimum	Maximum
Total N (%)	0.06	0.004	0.03	0.15
Organic carbon (%)	0.58	0.031	0.27	1.12
Soil organic matter (%)	1.01	0.054	0.46	1.95
Available P (mg g^{-1}) – Bray- I	0.01	0.001	0.00	0.02
Exchangeable K (mg g^{-1})	0.02	0.001	0.01	0.04
Exchangeable Ca (mg g^{-1})	0.48	0.039	0.06	0.93
Exchangeable Mg (mg g^{-1})	0.16	0.009	0.06	0.31
Exchangeable Na (mg g^{-1})	0.01	0.001	0.004	0.02
CEC ($cmol^+ kg^{-1}$)	5.41	0.244	2.20	10.07
pH ($CaCl_2$)	5.33	0.096	3.40	6.09
Sand (%)	61.20	1.539	43.88	81.88
Silt (%)	32.20	1.348	48.10	32.18
Clay (%)	6.60	0.320	2.04	11.28
Bulk density (g cm^{-3})	1.45	0.014	1.25	1.71

Conclusion

The soils of the study area are generally sandy in texture and characterized by low clay content and high sand content resulting in a poor structure.

The dominant sand and silt fractions of the soil are a result of deposits from the harmattan winds. Low values of CEC, SOM and intermediate quantities of exchangeable cations (K, Ca, Mg and Na) were observed in the soils. The soils are moderately acidic with very low organic carbon (< 1 %) and total nitrogen (< 0.1 %) and also P deficient.

5.2 Vegetation of study area

Sixty-nine plant species belonging to 23 families were encountered within the 49 sites sampled. In general, 48 % of the species identified were woody and 52 % herbaceous. In terms of growth form, 33 %, 15 %, 17 % and 35 % of the species were trees, shrubs, herbs and grasses respectively (Table 5.2).

The most common species were: *Vitellaria paradoxa, Combretum lamprocarpum, Terminalia avicennoides, Grewia mollis, Entada africana* and *Parkia biglobosa* (trees); *Nauclea latifolia, Tephrosia bracteolate* (shrubs); *Diodia scadens, Icaccina senegalensis* (herbs); *Andropogon gayanus, Hyperrhenia rufa, Hyperthelia dissoluta and Sporobolus pyramidalis* (grasses).

Table 5.2: Growth forms across study sites (September, 2002)

Growth form	No. of species	Percentage (%)
Trees	23	33.3
Shrubs	10	14.5
Herbs	12	17.4
Grasses	24	34.8
Total	69	100

5.2.1 Vegetation cover at landscape level

This section is devoted to the mapping of the vegetation types in the study area using remote sensing techniques.

The classified satellite image (Figure 5.1) suggests three broad vegetation types in the study area. In all, five broad land use and land cover classes were mapped. These are:

- Savanna woodland
- Open savanna woodland
- Mixture of grass/herb fallow and crop field
- Settlement
- Water body

The identified classes agree with the classification of the Ghana Land Cover and Land Use Classification scheme for visual classification of remotely sensed data designed by Agyapong et al. (1999). The categories are general, because the supervised classification algorithm (maximum likelihood classification) could not distinguish the image features into more detailed categories.

Lawson (1985), Benneh and Dickson (1988) and Willis (1962) described the vegetation of the Guinea savanna zone (the study area inclusive) as grassland with smaller or shorter, deciduous, fire-resistant, widely spaced branching trees. Cole (1986) and Stott (1991) also defined savanna as a tropical physiognomic vegetation type that consists of a continuous grass stratum, usually with a discontinuous stratum of either trees or shrubs. Observations in the field indicate that there is actually no pure grassland in the study area (as described in the structural analysis section), but a mixture of grasses and shrubs; however, there are isolated areas of pure grass cover, which are mostly fallowed or degraded areas, and woodlands with varying tree density. Typically, many of the trees are scattered without a close canopy in many places, enabling sufficient light to reach the ground for the growth of grass and shrubs as long as there is sufficient soil moisture Lawson (1985).

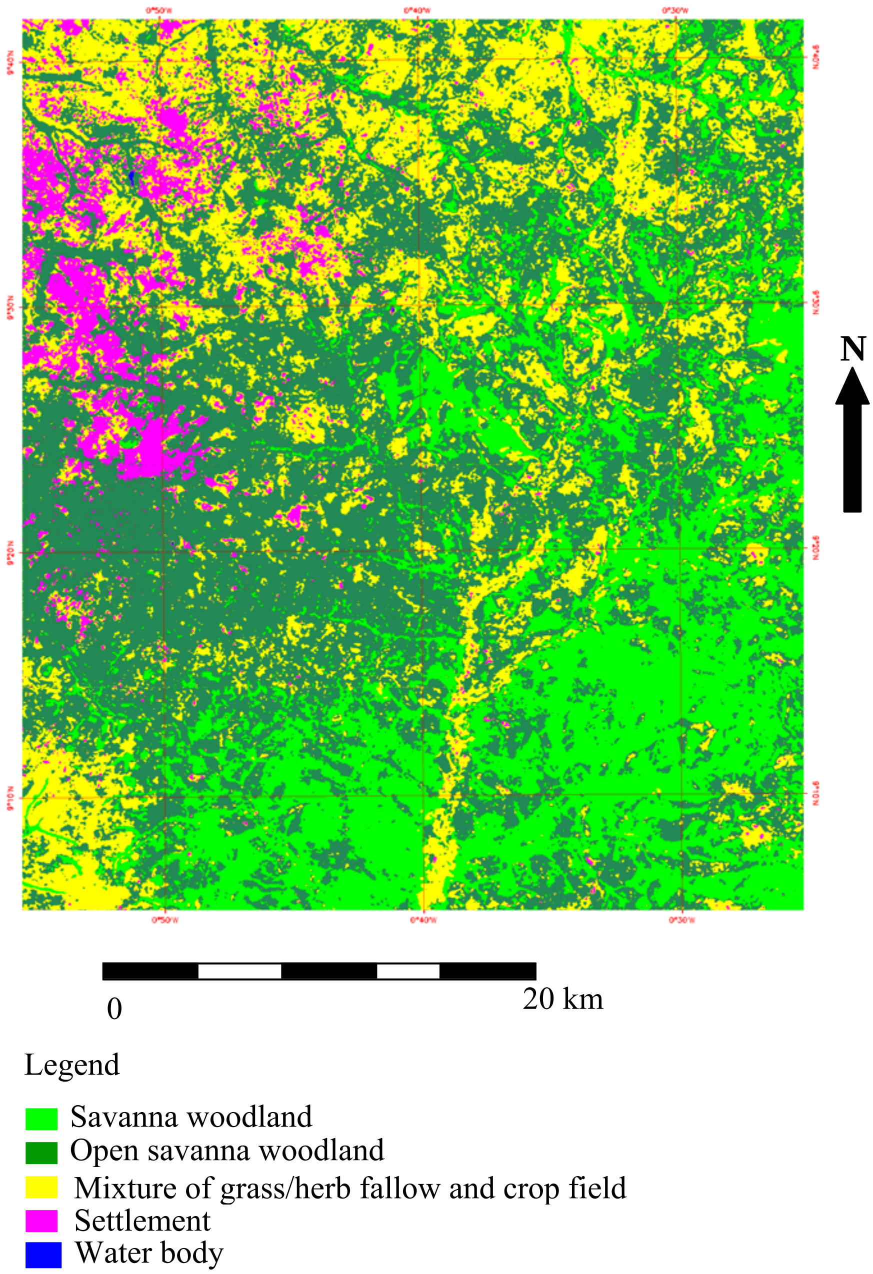


Figure 5.1: Map of vegetation type in study area. Classification performed on Landsat ETM + 7, 07/11/1999 using maximum likelihood algorithm

5.2.2 Structural analysis

Vegetation classification based on floristic composition largely ignores the physiognomy or structure of the vegetation. Vegetation communities can have similar species composition but different structure. This problem has been discussed by several authors, e.g., Westhoff (1967, 1968), Tüxen (1970a), Oberdorfer (1970), and Rejmanek (1977). Additionally, vegetation description based solely on remotely sensed information largely ignores the structural heterogeneity at site level. To address this problem, the Dansereau methodology was applied to collect quantitative and qualitative data at specific sites for structural description. Furthermore, only general categories were mapped out using remote sensing techniques, because the supervised classification algorithm (maximum likelihood classification) could not distinguish the image features into more detailed categories.

To this end, profile diagrams with their respective codes based on the scheme developed by Dansereau (Dansereau 1951, 1958; Dansereau et al., 1966; Dale 1979; Kent and Cooker, 2001) were drawn for all sampled sites in the study area (Appendix). These diagrams and codes adequately describe the external morphology, growth form, stratification and size of the plant species present.

The diagrams drawn from field observations portray the structure of the vegetation cover and depict structurally quite different vegetation types. Representative diagrams and their respective codes are drawn for the four types of vegetation identified in the cluster analysis (Figures 5.2, 5.4, 5.6 and 5.8).

5.2.3 Vegetation cover at site level

This section highlights the results of the vegetation description from the 49 sites within the landscape, which was statistically analyzed to identify the four vegetation groups in the study area.

Cluster analysis is an agglomerative hierarchical methodology that identifies clusters (groups) that contain relatively homogenous groups of observations (cases). In this study, cluster analysis was used to identify homogenous groups of sites based on selected qualitative (growth form, seasonality, leaf shape and texture) and quantitative (coverage and heights of trees, shrubs and herbs) vegetation characteristics.

Clustering of the 49 sites was done using the k-means algorithm (distance from cluster centers are calculated). The clustering distinguished four groups (Table 5.3) with 26 sites in cluster 1, 13 sites in cluster 2, 8 sites in cluster 3, and 2 sites in cluster 4.

The groups are: widely open savanna woodland, grass/herb fallow with scattered trees (75-150 trees ha^{-1}), open savanna woodland (75-150 trees ha^{-1}), and closed savanna woodland (>150 trees ha^{-1}).

The selected vegetation cover types for the fire experiment fall in section 4.2.1 can be related to the above groups as follows:

- Grass/shrub savanna belongs to widely open savanna woodland
- Grass and grass/tree savannas belong to the grass/herb with scattered trees
- Shrub savanna belongs to the open savanna woodland
- Tree savanna belongs to the closed savanna woodland.

Table 5.3: General characteristics of the groups of vegetation types identified

Cluster	Cluster Members	General cluster characteristics
1	Bontanga, Pishiegu, Lampoga, Bole-Bamboi Road (60th km mark), Timpella, Sadugu, Daboyiri, Karemenga, Gbimsi, Loagri, Nabogu, Kukobila, Gbambu, Gaa, Zinindo, Jariguyilli, Sinsini, Joronokponto, Damongo, Grupe, Kpalbusi, Massaka, Gbung, Sabonjida, Jaffour and Juni	Mixture of deciduous and semi-deciduous scattered trees and shrubs, with almost equal distribution. Have small, medium and sclerophyllous leaves. The sparse herbaceous stratum is dominated by grasses with sclerophyllous leaves and is mostly deciduous or ephemeral. This vegetation type belongs to the widely open savanna woodland vegetation (10-75 trees ha^{-1}).
2	Kadia, Janga, Gbadori, Nakoli, Kpandain, Nanton, Lansa-Kura, Larabanga, Kanantu, Sarikyekura, Salkpang, Sambu and Nyamaliga	Deciduous and semi-deciduous trees and shrubs interrupted and sparse, with small, medium and sclerophyllous leaves. The herb stratum dominates in this cluster and has continuous coverage most of which is grasses with sclerophyllous leaves. This vegetation type could be best described as grass/herb fallow with scattered trees (75-150 trees ha^{-1})
3	Tamaligu, Nyong, Nasuan, Gurugu, Jerimoape, Ntreso, Jagbajado, and Jimle	A mixture of deciduous and semi-deciduous dominated by shrubby vegetation, with mostly small, medium and sclerophyllous leaves. Barren and interrupted herb stratum dominated by grasses with sclerophyllous leaves. This vegetation type belongs to the open savanna woodland (75-150 trees ha^{-1}) with dense shrub.
4	Alhassan Kura and Dagomba-Line	Semi-deciduous woody vegetation trees dominated by tree stratum with mostly small, medium and sclerophyllous leaves. Herb stratum barren and interrupted with grasses dominating. The vegetation type could be described as closed savanna woodland (>150 trees ha^{-1}).

Table 5. 4: Mean coverage and height of trees, shrubs and herbs within vegetation types

Vegetation types	Coverage (%)			Height (m)		
	Tree	Shrub	Herbs	Tree	Shrubs	Herbs
Widely open savanna woodland	7	12	8	4.0	1.6	1.9
Grass/herb fallow with scattered trees	8	7	65	3.8	1.2	1.0
Open savanna woodland	3	64	30	1.8	1.6	0.8
Closed savanna woodland	55	25	5	4.0	1.5	0.5

The woody plants (trees and shrubs) largely determined the four vegetation types recognized in this study area with a grass dominated herb stratum. The results of the cluster analysis grouped the sites based on the coverage and heights of the growth forms (trees, shrubs and herbs) quantified in each site (Table 5.4). Generally the coverage ranged from 3 % to 65 % and the heights from 0.5 m to 4.0 m.

Widely open savanna woodland

The structure of the widely open savanna woodland vegetation type is presented in Figure 5.2; the symbols represent the various growth forms and their respective codes as identified on the field. The vegetation cover here was very low. The woody plants contributed about 32 % coverage with a height between 2-4 m. The herb stratum reached up to 1.5 m in height and contributed about 8 % coverage. Figure 5.3 is representative of the vegetation cover of the widely open savanna woodland as observed in the field; the vegetation cover is interrupted by bare surfaces and widely scattered trees.

The widely open savanna woodland has developed through the continuous and intensive exploitation of the open savanna woodland for timber or fuel wood, other products and incessant fire as well as for agricultural purposes. This is the most common or expansive vegetation type in the study area (Table 5.3) and found almost everywhere. It is found mostly in areas that have been farmed for a long time and where the economic trees have been left on the land.

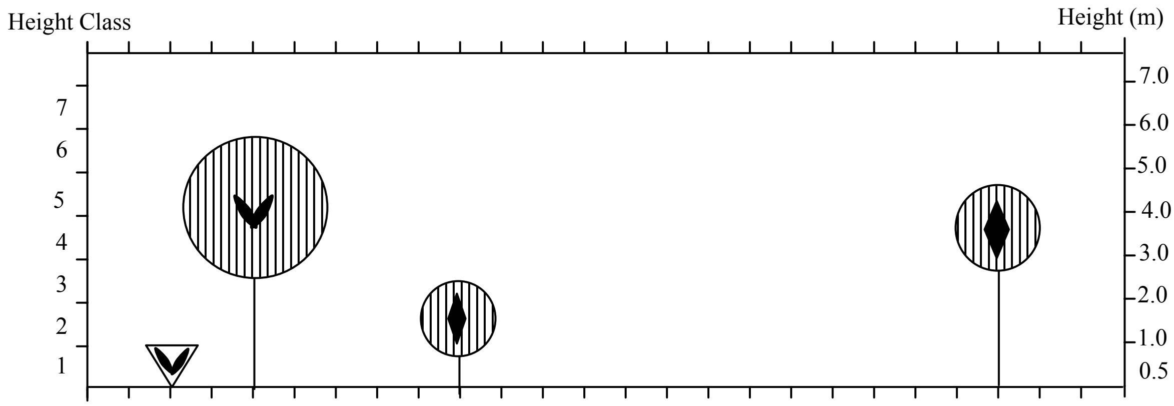


Figure 5.2: Structural diagram of widely open savanna woodland; for details see chapter 4 (cluster 1 in Table 5.3) W6svxb, W4saxb, W3saxb, H2dvxb (structural codes according to Dansereau, 1958); *Vitellaria paradoxa*, *Tephrosia bracteolate* and *Diodia scadens*

Figure 5.3: Widely open savanna woodland (cluster 1 in Table 5.3)

Grass/herb fallow with scattered trees and shrubs

The structure of the grass/herb fallow with scattered trees and shrubs vegetation type is presented in Figure 5.4. The different vegetation structure coverage ranged from 8-76 %. The woody plants cover was very sparse and about 12 % with a height up to 7 m.
The herb stratum (dominated by grass) was quite dense (Figure 5.5) with coverage of about 65 % and up to 2.5 in height.

The vegetation type grass/herb fallow with scattered trees and shrubs has developed as a result of human intervention involving the clearing of the closed and open savanna woodland areas for cultivation and left to fallow. It is always found in association with farmlands; edaphic factors may have also contributed to its formation.

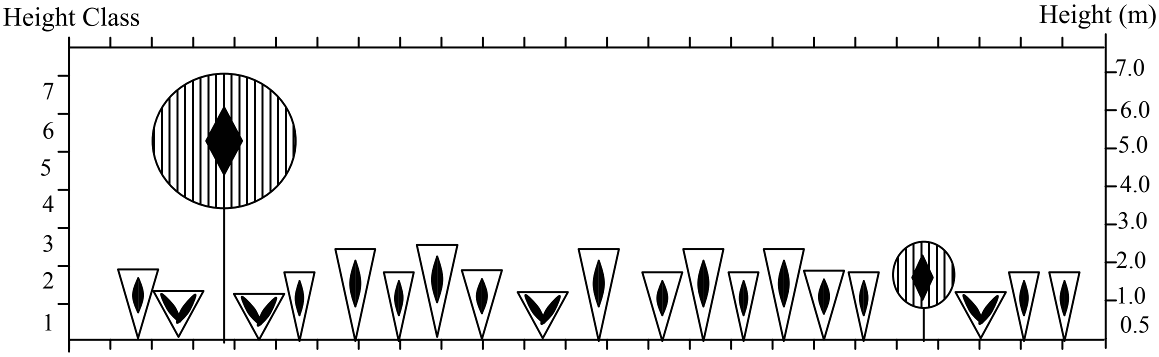


Figure 5.4: Structural diagram of grass/herb fallow with scattered trees and shrubs; for details see chapter 4 (cluster 2 in Table 5.3), W7saxi, W2saxb, H3dgxc, H2dg (v)xc (structural codes according to Dansereau, 1958); *Vitellaria paradoxa*, *Tephrosia bracteolate, Diodia scadens, Andropogon gayanus, Hyperrhenia rufa, Hyperthelia dissolute*

Figure 5.5: Mixture of grass/herb fallow with scattered trees and shrub (cluster 2 in Table 5.3)

Open savanna woodland

The structure of the open savanna woodland is illustrated by Figure 5.6. The plant cover varies between 3 – 65 %; woody plant cover was about 64 % and up to 6 m in height. The herb stratum was sparse and about 12 % and up to 1.5 m in height. Figure 5.7 illustrates a typical example of the open savanna woodland as observed on the field.

The open savanna woodland vegetation type is the result of the conversion of closed savanna woodland due to exploitation such as for timber or fuel wood as well as of bushfire. The exploitation here is not as intense as in the case of the widely open savanna woodland, but is always found in association with the widely open savanna woodland.

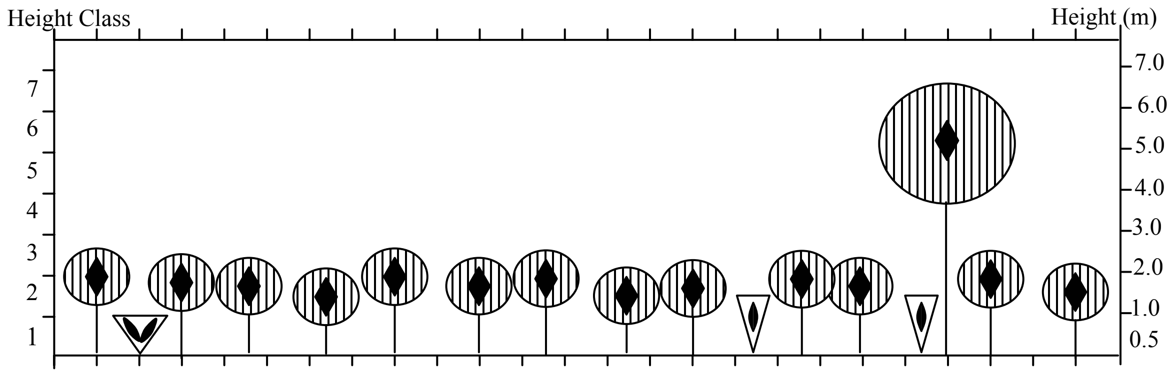


Figure 5.6: Structural diagram of open savanna woodland dominated by shrubs; for details see chapter 4 (cluster 3 in Table 5.3). W7saxb, W3saxc, H2dg (v)xb (structural codes according to Dansereau, 1958); *Vitellaria paradoxa, Tephrosia bracteolate, Annona senegalenses, Diodia scadens, Andropogon gayanus, Hyperrhenia rufa, Pennisetum sp.*

Figure 5.7: Open savanna woodland vegetation dominated by shrubs (Cluster 3 in Table 5.3)

Closed savanna woodland

The structure of the open savanna woodland is illustrated by Figure 5.8. The vegetation cover of this woody plant cover is about 80 % and up to 7 m and above. The herb stratum is about 12 % and 1.5 m in height. Figure 5.9 illustrates a typical example of the closed savanna woodland as observed on the field.

The closed savanna woodland is mostly restricted to reserved lands. However, some of these woodlands have been intensively degraded because of the higher population densities in these areas. This agrees with the observation of Contreras-Hermosilla (2000) and Schroth and Sinclair (2003) that population growth contributes to the degradation of forests and woodlands because of the increased clearing of land for farming and exploitation of wood for construction and fuel wood.

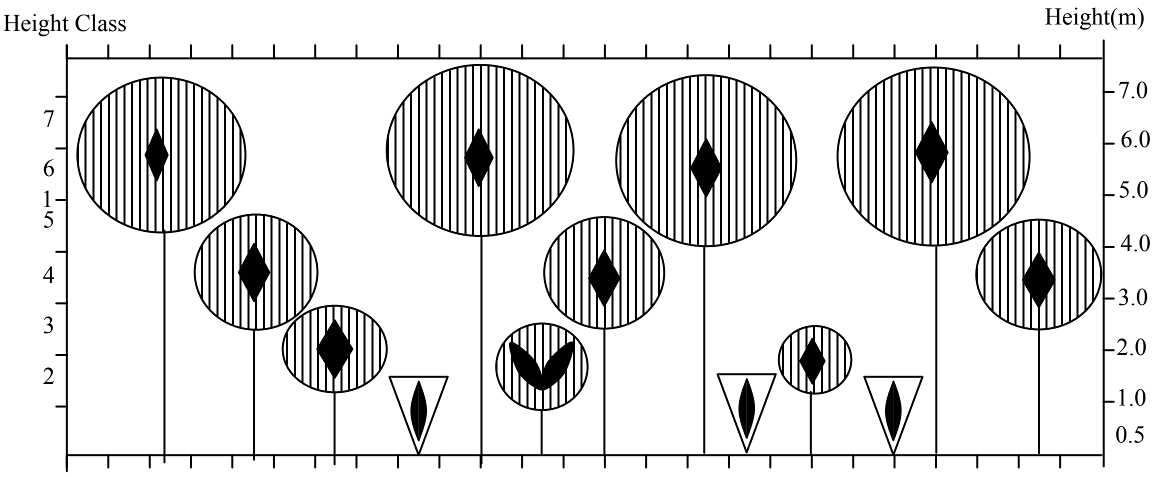


Figure 5.8: Structural diagram of closed savanna woodland dominated by trees; for details see chapter 4 (cluster 4 in Table 5.3).W7saxc, W5saxc, W2sa(v)b, H2dgxb (structural codes according to Dansereau, 1958); *Vitellaria paradoxa Lannea acida, Nauclea latifolia*, *Andropogon gayanus, Hyperrhenia rufa, Pennisetum spp.*

Figure 5.9: Closed savanna woodland (cluster 4 in Table 5.3)

Vegetation dynamics

The vegetation of the study area has changed over the years due to human intervention. Hopkins (1981) suggests that the heterogeneous vegetation cover of the Guinea savanna zone (the study area inclusive) can be attributed to annual burning, cropping and grazing.

During cultivation, trees and shrubs are cut down. Some shrubs, however, are left and used as stakes for yam. Prolonged sequences of farming periods with shorter bush fallow have led to a considerable decrease in trees and those that remain are largely confined to trees considered to be useful or restricted to sacred groves and wildlife reserves. In northern Ghana, the livestock density is high. This has lead to overgrazing in some areas and the reduction of vegetation cover has lead to soil erosion.

Immediately after the dry season bushfires, the study area looks devastated. The trees and shrubs are leafless and have charcoal-blackened barks. All the remains of the herb stratum are few charred remains of unburnt grass and a layer of ash on the soil surface. Fire severely damages many of the woody plants; some fire resistant species, however survive. The damage is increased with the intensity of the burning both in terms of frequency and intensity.

Westhoff (1967, 1968) observed that extreme habitat factors like frequent burning can lead to the phenomenon of floristically very similar but structurally quite different “twin formations”. Overgrazing and trampling by livestock are also regarded as destructive habitat factors by Werger (1973b), and often result in reduction of grass cover, soil erosion and bush encroachment. Cutting of wood for fuel is a common practice in the study area. This has led to not only to changes in species composition but also to changes in vegetation structure and deterioration of the vegetation.

Summary and conclusion

Generally, five broad land cover and land use types were identified at the landscape level in the study area using remotely sensed data. These land cover types are: savanna woodland, open savanna, mixture of grass/herb fallow and crop fields, settlement and water body.

At the site level, profile diagrams with codes adequately describe the vegetation structure of the landscape and categorise into four broad structural groups.

These groups are: widely open savanna woodland, grass/herb fallow with scattered trees (75-150 trees ha^{-1}), open savanna woodland (75- 150 trees ha^{-1}) and closed savanna woodland (>150 trees ha^{-1}). Furthermore, these diagrams with their respective codes describe the external morphology, growth form, stratification and size of the plant species present.

This study shows how the physiognomic method by Dansereau was used to adequately describe the vegetation structure of the study area. Observations in the field indicate that there are actually no pure stands in the study area but rather a mixture of grasses, shrubs and trees; however there are isolated areas of grass cover, which are mostly fallowed or degraded areas, and woodlands with varying tree density. Typically, many of the trees are scattered without a close canopy in many places, enabling sufficient light to reach the ground for the growth of grass and shrubs as long as there is sufficient soil moisture.

5.3 Bushfire experimental sites

5.3.1 Site characteristics

Five sites with different vegetation cover types namely: shrub savanna, grass savanna, grass/shrub savanna, grass/tree savanna and tree savanna were selected for the bushfire experiment. At each site, the physicochemical properties of the soils (Table 5.5) as well as the floristic composition (Table 5.8) were determined.

The soil texture ranged from sandy loam to loamy sand (Landon, 1991) and bulk density from 1.25 – 1.59 g cm^{-3}. Exchangeable cations (K, Ca, Mg and Na) were rated reaching or above the critical range (Landon, 1991). This is consistent with a study by Fugger (1999) from the Guinea agroecological zone. The soils are moderately acidic with the tree savanna having the highest pH of 5.8. Soil organic carbon and total nitrogen were less than 2 % and 0.1 %, respectively. The phosphorus content of the sites is rated as P deficient and agrees with Tiessen and Abekoe (1998) and Fugger (1999).

The grass savanna is dominated by grass and characterized by deciduous and semi-deciduous trees and shrubs, interrupted and sparse, with small and medium sclerophyllous leaves (< 10 trees ha^{-1}). The herb stratum dominates and shows continuous coverage most of which are grasses with sclerophyllous leaves.

Shrub savanna comprises a mixture of deciduous and semi-deciduous shrubby vegetation, with mostly small and medium sclerophyllous leaves. The partly barren and interrupted herb stratum is dominated by grasses with sclerophyllous leaves (75-150 trees ha^{-1}). Grass/shrub savanna is a mixture of grass and shrubs with scattered trees. The herb stratum dominates and shows continuous coverage, most of which is grasses with sclerophyllous leaves (75-150 trees ha^{-1}). The grass/tree savanna (< 25 trees ha^{-1}) is a mixture of grass and trees, the herb stratum dominates and shows continuous coverage, most of which is grasses with sclerophyllous leaves. The tree savanna (>150 trees ha^{-1}) with semi-deciduous woody vegetation is dominated by the tree stratum with mostly small and medium sclerophyllous leaves. The herb stratum is partly barren and interrupted with grasses dominating (>150 trees ha^{-1}).

Table 5.5: Physicochemical properties of selected sites for fuel and fire experiment (August 2002, soil depth -10cm)

Soil parameter	Shrub savanna	Grass savanna	Grass/shrub savanna	Grass/tree savanna	Tree savanna
Total N (%)	0.12	0.05	0.08	0.05	0.05
Organic carbon (%)	1.14	0.53	0.59	0.34	0.49
Organic matter (%)	1.95	0.92	1.02	0.67	0.84
Available P (mg g^{-1}) – Bray- I	0.01	0.02	0.01	0.010	0.01
Exchangeable K (mg g^{-1})	0.03	0.02	0.02	0.011	0.02
Exchangeable Ca (mg g^{-1})	0.67	0.52	0.43	0.47	0.47
Exchangeable Mg (mg g^{-1})	0.28	0.13	0.11	0.11	0.11
Exchangeable Na (mg g^{-1})	0.01	0.01	0.003	0.003	0.003
CEC ($cmol^{+}$ kg^{-1})	7.01	4.94	4.14	4.24	3.96
pH ($CaCl_2$)	5.50	5.60	5.59	5.61	5.80
Sand (%)	54.9	48.9	56.9	72.9	68.9
Silt (%)	35.8	45.8	33.8	21.8	26.8
Clay (%)	9.30	5.30	9.30	5.30	4.30
Bulk density (g cm^{-3})	1.52	1.40	1.59	1.25	1.53

Twenty-eight dominant species (Table 5.6) were identified in the five vegetation cover types identified, where 45 % are herbaceous.

Table 5.6: Floristic composition of the five different vegetation cover types where fuel load and fire experiment were carried out

Species name	Family	GF	SS	GS	GSS	GTS	TS
Andropogon gayanus	Poaceae	g	x	x	x	x	
Andropogon tectrum	Poaceae	g	x	x			
Annona senegalensis	Annonaceae	s			x		
Aristida adcencious	Poaceae	g					x
Combretum lamprocarpum	Combretaceae	t		x		x	
Chamaecrista mimosoides	Fabaceae	s		x			
Detarium microcarpum	Fabaceae	s	x				x
Digitaria horizontalis	Poaceae	g			x		
Diodia scadens	Rubiaceae	h			x	x	
Entada Africana	Fabaceae	t	x	x	x		x
Gardenia ternifolia	Rubiaceae	t	x				
Grewia mollis	Tiliaceae	t	x	x	x		x
Heteropogon contortus	Poaceae	g					x
Hyperrhenia rufa	Poaceae	g				x	x
Hyperthelia dissolute	Poaceae	g				x	x
Lannea kersiingii	Anacardiaceae	t	x				
Monechma ciliatum	Acanthaceae	h	x				
Nauclea latifolia	Rubiaceae	s				x	
Parkinsonia aculeate	Fabaceae	t		x			
Pennisetum spp	Poaceae	g		x			
Piliostigma thonningii	Fabaceae	t			x		
Pterocarpus erinaceus	Fabaceae	t		x		x	
Schizachyrium exile	Poaceae	g				x	
Securinega virosa	Euphorbiaceae	s				x	
Tephrosia bracteolate	Fabaceae	s	x		x	x	
Tephrosia pedicellata	Fabaceae	s	x				x
Terminalia avicennioides	Combretaceae	t				x	x
Vitellaria paradoxa	Sapotaceae	t		x	x	x	

GF =Growth form, SS = Shrub savanna, GS =Grass savanna, GSS= Grass/shrub savanna, GTS= Grass/tree savanna, TS= Tree savanna, g= grass, h= herb, s = shrub and t = tree

5.3.2 Weather conditions and fire behavior

Table 5.7 presents the physical factors describing wind speed and wind direction, and the conditions such as humidity and temperature. The wind speed ranged from 1.7 to 4.5 m s^{-1}, whereas duration of fire was from 3 to 45 min, i.e., wind speed was inversely proportional to duration of fire. The wind speed and direction greatly influenced the evolution of the fire. The fires started on the experimental plots were headfires, i.e., fire spreading in the direction of the wind; higher wind speeds cause headfires to spread faster, as compared to backfires which are slower. Wind speeds between 2 – 6 m s^{-1} cause a faster spread of fire and influence wild fires occurring in an open savanna (Beer, 1991); similar values (1.7 to 4.5 m s^{-1}) were, however, measured in this study.

The temperature of the fire measured at the experimental sites ranged between 303 ^{o}C to 520^{o}C. Measurements made by van de Vijver (1999) in the East African savanna are in accordance with the ranges obtained in this study. Comparable values have also been reported in similar environments (West, 1965; Boo et al., 1996; Whelan, 1995; Morgan, 1999).

Table 5.7: Date, duration, speed and direction of fire during early and dry season burning from different vegetation cover sites in northern Ghana as measured on the day of ignition. All values refer to the conditions at the time of the burns

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
	Dec	Feb	Dec	Feb	Dec	Feb	Dec	Feb	Dec	Feb
Date and time of fire	1/12/02 13: 30	5/2/03 13: 30	11/12/02 13: 20	4/2/03 13: 20	9/12/02 13: 20	7/2/03 13: 00	5/12/02 12: 30	9/2/03 13: 05	04/12/02 13: 20	13/2/03 13: 00
Duration of fire (minutes)	10	5	10	3	16	7	45	4	7	10
Wind direction	E	S	W	W	W	W	S	E	NW	E
Wind speed (ms^{-1})	2. 5	4. 5	2. 5	5. 0	2. 3	2. 5	1.7	4.0	3. 3	2. 7
Temperature of fire	nd	308-402	nd	327-398	nd	303-520	nd	458-511	nd	314-395

nd = no data, instrument was not available

The duration of the fire was longer at the beginning of the dry season (December 2002) than late in the season (February 2003) and, conversely, wind speed was higher in late than in the early dry season with the exception of the tree savanna site. The reason for these trends is that, when the wind speed is higher, the fire spreads very fast and the burning time is shorter. The exceptionally long duration of burn measured in the grass/tree savanna site was due to the higher moisture content of the fuel load. The grass/tree savanna site appeared to be a waterlog area, and the availability of residual moisture delayed the drying of plants; this was not observed in other sites, which were relatively dry.

5.4 Fuel load assessment

5.4.1 Fuel load and ash

Fuel load in this study is defined as all combustible aboveground vegetative matter (excluding the stems of standing shrubs and trees). This includes; dead and fallen leaves, fruits and seeds originating from trees and grass, herbs, standing grass, downed woody debris or twigs, foliage on small trees and shrubs.

The results of the analyses of the fuel load components and ash content for the two periods (early and late dry season) are presented in Table 5.8. The early dry season sampling shows variations in fuel load and contribution of the components across the sites, with the grass component contributing over 60 % of the total fuel load (Table 5.8). The shrub savanna had the lowest grass biomass, and this was significantly different from the values of the other vegetation cover types. The leave component was higher in the shrub savanna (0.74 t ha^{-1}) and significantly different ($P < 0.01$) from the grass savanna, which had the lowest value (0.11 t ha^{-1}). Similarly, the shrub savanna site had the highest twig component (1.03 t ha^{-1}), which was significantly different from that of the grass savanna (0.23 t ha^{-1}).

Table 5.8: The total fuel load and carbon prior to burning, remaining in ash, and carbon content in ash and subsequent losses in different vegetation covers in Northern Ghana (Dec. 2002 and Feb. 2003). Values are mean; standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna		Sig. Level	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
Fuel load (t DM ha^{-1})												
Grass	3.27^{B}	1.58^{b}	6.23^{A}	5.76^{a}	5.18^{A}	1.69^{b}	5.03^{A}	5.13^{a}	4.88^{A}	2.37^{b}	<0.01	<0.01
	(0.23)	(0.10)	(0.25)	(0.33)	(0.46)	(0.15)	(0.52)	(0.60)	(0.33)	(0.24)		
Leaves/Litter	0.74^{A}	1.48^{b}	0.11^{C}	1.96^{a}	0.29^{BC}	1.11^{b}	0.52^{AB}	1.38^{a}	0.42^{ABC}	1.11^{b}	<0.01	<0.03
	(0.16)	(0.16)	(0.03)	(0.14)	(0.03)	(0.14)	(0.08)	(0.18)	(0.08)	(0.14)		
Twigs	1.03^{A}	0.18^{b}	0.23^{B}	0.10^{b}	0.57^{AB}	0.01^{b}	0.69^{AB}	0.53^{a}	0.64^{AB}	0.34^{ab}	<0.03	<0.01
	(0.23)	(0.02)	(0.04)	(0.03)	(0.18)	(0.008)	(0.16)	(0.14)	(0.19)	(0.12)		
Total	4.99	3.36^{b}	6.74	7.80^{a}	6.05	2.81^{b}	6.51	7.03^{a}	6.08	3.79^{b}	NS	<0.01
	(0.45)	(0.19)	(0.29)	(0.40)	(0.55)	(0.13)	(0.58)	(0.64)	(0.42)	(0.29)		
Carbon in fuel load	2.27	1.58^{b}	2.95	3.49^{a}	2.79	1.36^{b}	2.88	3.13^{a}	2.61	1.84^{b}	NS	<01
	(0.22)	(0.11)	(0.19)	(0.02)	(0.26)	(0.07)	(0.26)	(0.3)	(0.17)	(0.14)		
Ash mass (t DM ha^{-1})												
Fine ash (<mm)	0.34^{B}	0.62^{ab}	0.73^{A}	0.57^{b}	0.24^{B}	0.78^{ab}	0.29^{B}	0.92^{a}	0.62^{A}	0.72^{ab}	<0.01	<0.01
	(0.02)	(0.07)	(0.06)	(0.05)	(0.01)	(0.08)	(0.05)	(0.11)	(0.06)	(0.04)		
Coarse ash (>mm)	0.11^{C}	0.34	0.51^{A}	0.21	0.28^{B}	0.39	0.29^{B}	0.42	0.27^{A}	0.62	<01	NS
	(0.01)	(0.06)	(0.03)	(0.04)	(0.03)	(0.06)	(0.04)	(0.04)	(0.03)	(0.02)		
Total	0.45^{C}	0.97	1.24^{A}	0.78	0.52^{C}	1.17	0.58^{C}	1.34	0.88^{B}	0.98	<0.01	NS
	(0.03)	(0.13)	(0.08)	(0.08)	(0.03)	(0.01)	(0.09)	(0.02)	(0.09)	(0.08)		
Carbon in ash	0.13	0.15	0.31	0.09	0.15	0.15	0.14	0.13	0.18	0.06		
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.05)	(0.02)	(0.02)	(0.02)	(0.004)		
Losses (t DM ha^{-1})												
Fuel load	4.53	2.39^{b}	5.5	7.02^{a}	5.52	1.64^{b}	5.93	5.69^{a}	5.20	2.82^{b}	NS	<0.01
	(0.45)	(0.27)	(0.34)	(0.41)	(0.57)	(0.19)	(0.58)	(0.68)	(0.41)	(0.35)		
Carbon	2.16	1.42^{b}	2.64	3.39^{a}	2.64	1.21^{b}	2.77	3.00^{a}	2.43	1.76^{b}	NS	<0.01
	(0.22)	(0.11)	(0.29)	(0.23)	(0.26)	(0.07)	(0.24)	(0.31)	(0.16)	(0.15)		
Relative losses (%)												
Fuel load	91	71	82	90	91	58	91	81	85	74		
	(1.29)	(3.66)	(1.85)	(1.31)	(1.57)	(1.79)	(1.84)	(3.29)	(1.58)	(4.12)		
Carbon	95	90	89	97	95	89	96	96	93	96		
	(1.18)	(1.93)	(1.14)	(0.49)	(1.37)	(2.15)	(0.84)	(1.07)	(0.76)	(1.27)		

NS= Non-significant. Values with different superscripted capital and small letters denote significant difference in total fuel load across the five sites prior to burning for December and February respectively. DM= dry matter

The average total fuel loads varied between 4.99 and 6.74 t ha^{-1} but not significantly across the sites. The total mass of fuel load burnt in the early dry season was between 4.50 and 5.90 t ha^{-1}, with the grass/tree savanna giving the highest loss and the shrub savanna the lowest. However the relative percentage loss was between 82 % and 90 % of the harvested fuel load in the December 2002 period (Table 5.8). The differences observed were influenced by varying physical factors such as wind speed, temperature of fire, its intensity and duration.

During the late dry season (February 2003), the total fuel load ranged from 3.36-7.80 t ha^{-1}, with grass biomass contributing an average of 63 % (Table 5.8). The highest average fuel load was at the grass savanna site (7.80 t ha^{-1}), which was significantly different from the grass/shrub savanna site which had the lowest fuel load (2.81 t ha^{-1}). The mean fuel load consumed by fire (combustion factor or combustion efficiency) was variable across the different vegetation cover types (Tables 5.8). The losses from these vegetation covers were between 2.40 and 7.02 t ha^{-1}, and the percentage loss ranged from 58% to 90% for the late dry season period. These differences are attributed to incomplete combustion as was observed on the field and in the composition of the remaining ash component in the tray and on the soil surface.

The high fuel load measured at the grass savanna and grass/tree savanna sites is due to the fact that the vegetation structure is dominated by a herbaceous stratum, mainly grasses, which is the major contributor to the total fuel load. In contrast, the shrub savanna, grass/shrub savanna and tree savanna had a low fuel load due to their low herbaceous strata and relatively high tree and shrub coverage.

The fuel loads measured in this study appear to be representative of most savanna areas and are comparable to those reported elsewhere in Africa. For example, Saarnak (1999) recorded between 2 and 3 t ha^{-1} in northern Ghana, Shea et al. (1996) measured 3.7 t ha^{-1} in the savannas of South Africa, Laclau et al. (2002) 5.19 t ha^{-1} in the Congo, Fournier (1991) 5.2 to 7.9 t ha^{-1} in West Africa, and 3.2 – 4.4 t ha^{-1} were reported by Bourliére and Hardly (1983) at Lamto in the savanna zone of the Ivory Coast.

The range of fuel load found at the study sites is comparable to those reported from savannas elsewhere in the world. For example, Cheney et al. (1993) reported 2 to 6 t ha^{-1} for grassland savanna, Bowman and Wilson (1988) measured 6.3 t ha^{-1} in eucalypt savanna, Mott and Andrew (1985) reported grass fuel levels of 2 to 4 t ha^{-1}, and Kauffman et al. (1994) recorded similar results in South America.

The deposition of ash after fire was heterogeneously distributed over the different vegetation cover types in both the early and late dry season (Table 5.8). Generally, the ash was dominated by the fine ash fraction (< 1 mm) with the exception of the grass/shrub savanna, which produced coarser ash in the early dry season. Coarse and fine ash fractions were, however, equal in tree savanna within the same season. This indicates that the efficiency of burning (quality) in the shrub savanna may have been lower due to the dominant woody vegetation (shrubs), which does not burn in this savanna. The mean amount of total ash mass varied from a high of 1.34 t ha^{-1} in the grass/tree savanna to a low of 0.45 t ha^{-1} in the shrub savanna. The variability was large across the vegetation cover types and this explains the high standard error observed. The most likely reason for the variability was due to the windy nature of the environment during the bushfire. These winds carried away a substantial amount of ash. The heterogeneous distribution in the plot of the burnt fuel load could also be responsible for the variability.

When relating the total fuel load before burning and the total mass of ash after burning, it becomes evident that the bushfire consumed between 4.5 t ha^{-1} and 5.8 t ha^{-1} of the fuel load with grass/tree savanna being the highest and shrub savanna the lowest in the early dry season. However, in the late dry season, fuel losses ranged from 2.4 to 7.0 t ha^{-1} (71 and 90 % of total fuel load, respectively). The grass savanna had the highest value of 7.0 t ha^{-1}, which was significantly different from that of the shrub (lowest 2.4 t ha^{-1}), grass/shrub and tree savannas, but similar to the grass/tree savanna.

5.4.2 Carbon pool

The carbon concentrations were variable across the vegetation cover types and in fuel load components, but did not show any particular trend in early and dry season samples. Carbon concentration ranged from 42 - 50 % among the fuel load components (Table 5.9).

The C concentration of fine ash across the vegetation cover types varied from 6 - 18 % with grass/tree savanna and tree savanna recording the lowest and highest, respectively. While coarse ash ranged from 13 to 39 %, with the shrub vegetation showing the lowest and grass vegetation the highest.

Table 5.9: Carbon concentrations of fuel load and ash from different vegetation cover types in northern Ghana (December 2002 and February 2003). Values are means; standard error in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(%)									
Grass	44 (2.3)	50 (1.3)	44 (1.5)	44 (2.0)	46 (1.5)	49 (0.3)	47 (2.2)	44 (1.5)	44 (2.5)	48 (0.5)
Leaves/Litter	48 (1.9)	48 (0.5)	45 (1.9)	46 (1.3)	48 (1.25)	48 (0.5)	43 (1.4)	44 (1.9)	45 (2.8)	47 (1.8)
Twigs	47 (1.9)	49 (34.1)	47 (2.7)	45 (1.6)	42 (1.9)	45 (0.6)	45 (2.1)	43 (1.3)	42 (1.7)	50 (3.0)
Fine ash	17 (2.0)	12 (1.2)	17 (2.1)	13 (1.2)	18 (1.3)	9.3 (0.6)	10 (1.8)	5.7 (0.7)	18 (0.4)	8.3 (3.9)
Coarse ash	39 (2.8)	21 (1.1)	39 (2.4	13 (1.2)	38 (1.6)	20 (1.3)	29 (5.4)	19 (1.9)	25 (2.4)	15 (4.7)

Concentration of C was lower in the fine ash than in the coarse ash (Table 5.9). This is reasonable since the level of combustion in the fine ash is higher than in the coarse ash. Combustion is relatively incomplete in coarse ash as compared to that of fine ash.

The total C stocks across the different vegetation cover types were variable. The highest C stock was measured in grass savanna (2.95 t ha^{-1}) and was not significantly different from shrub savanna with the lowest (2.27 t ha^{-1}) in the early dry season period. During the late dry season period, grass savanna recorded the highest (3.49 t ha^{-1}); this was significantly different from the lowest, i.e., grass/shrub savanna (1.36 t ha^{-1}). The variations in fuel load, especially the grass biomass (Table 5.8), as well as the concentration of carbon in its respective components (Table 5.9) to a large extend determined the total carbon stocks observed in each of the vegetation cover types and explains the significant differences across the vegetation cover types. As expected, the C stocks paralleled total fuel load.

Loss of C was quite high, as 1.21- 3.39 t ha^{-1} was lost due to the fires representing between 89 and 97 % of the total fuel load (Table 5.8). The highest loss occurred in grass savanna and the lowest in grass/shrub savanna across the vegetation cover types and seasons. The massive loss of carbon is associated with the low volatilization temperature (T < 400^{o}C; Lide, 1998); temperatures between 400 ^{o}C and 500 ^{o}C were measured in the study area. Wind erosion might have contributed to some of the losses through ash convection.

5.4.3 Seasonal patterns of fuel load fluxes

The seasonal changes in fuel loads and composition (grass: leaf ratios) are a consequence of the leaf phenology of the trees within the tropical savanna. Whilst deciduous trees commence leaf fall early in the dry season, semi-deciduous have peaks of leaf fall later in the dry season (Wilson et al., 1995; Williams et al., 1997). Hence, by the late dry season, the proportion of leaf components of the fuel load has increased (Table 5.8). However, no consistent pattern was observed for the total fuel load. The shrub savanna, grass/shrub savanna and tree savanna decreased from the early dry season to the late dry season with the differences for shrub and grass/shrub savannas being significant (paired t-test, $p < 0.01$, $n = 10$), but that of tree savanna was not significant. Though the values for grass savanna and grass/tree savanna increased, they are not significant (Table 5.8). The lower fuel load measured in the late dry season for shrub, grass/shrub and tree savannas could be due to excessive grazing by goats and sheep that was observed during the second sampling at these sites, but which was absent at the grass and grass/tree savannas sites. The grass and grass/tree savannas were comparatively moist, and there may have been an increase in dry matter between the first and second samplings.

Generally, the fuel load and carbon losses were higher in the early dry season bushfires (Table 5.8). A higher fuel load was burnt and lost from the sites early in the dry season than late in the dry season with the exception of grass savanna. In the shrub, grass/shrub and tree savannas, the differences were significant (paired t-test, $p < 0.05$, $n = 10$), that of the grass/tree savanna was insignificant. The grass savanna was the only location that showed significant increases in losses in the late dry season. Similar trends were observed in terms of losses of carbon between the two seasons. Patchiness and discontinuous nature of fuel load distribution in the plots in the different vegetation cover types affected the quality of burn (combustion efficiency); this is largely responsible for the lower losses recorded in the late dry season bushfires.

Summary and conclusion

Quantity and quality of fuel load is influenced by the vegetation cover type. Grass was the major contributor to fuel load in all different vegetation cover types. The fuel load was highest (7.8 t ha^{-1}) in the herbaceous dominated plant communities, and about 58 to 91% of the fuel load was burnt. Generally, the ash was dominated by the fine ash fraction (< 1 mm). Carbon concentration ranged from 42 - 50 % among the fuel load components, the concentration of C in fine ash was lower (6 - 18 %) than in coarse ash (13 to 39 %). The total C stock was 1.36 - 3.49 t ha^{-1} and relative losses were 89 to 97 % in the study area. It was observed that the season did not show any consistent pattern for the fuel load and carbon dynamics.

5.5 Nutrient fluxes

5.5.1 Nutrient concentrations of fuel load and ash

The nutrient concentrations were variable across the different vegetation cover types and in fuel components, but did not show any particular trend in both seasons (Tables 5.10–5.15). Typically, the nitrogen concentration was higher in leaves and litter than in the twig components and ranged from 3.0 – 8.7 mg g^{-1} (Table 5.10).

Table 5.10: Nitrogen concentrations of fuel load and ash from different vegetation cover types in northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(mg g^{-1})									
Grass	4.1 (0.20)	4.6 (0.30)	3.6 (0.10)	3.6 (0.20)	4.3 (0.20)	5.0 (0.30)	4.0 (0.20)	3.3 (0.10)	3.1 (0.10)	4.2 (0.01)
*Leaves/litter	7.5 (0.40)	5.5 (0.50)	8.7 (0.70)	3.1 (0.06)	6.9 (0.80)	5.3 (0.20)	8.1 (0.70)	5.1 (1.20)	7.3 (0.50)	5.2 (0.20)
Twigs	4.9 (0.40)	6.6 (0.50)	6.0 (0.30)	4.1 (0.60)	3.8 (0.20)	4.9 (0.10)	3.8 (0.50)	3.0 (0.20)	4.4 (0.36)	5.8 (0.10)
Fine ash	1.7 (0.07)	1.5 (0.10)	1.2 (0.10)	3.3 (0.40)	1.5 (0.06)	0.9 (0.09)	0.9 (0.10)	1.8 (0.20)	0.9 (0.10)	1.8 (0.50)
Coarse ash	6.9 (0.20)	1.8 (0.10)	2.3 (0.20)	3.3 (0.40)	6.2 (0.30)	1.8 (0.10)	3.8 (0.60)	5.2 (0.30)	4.2 (0.20)	3.8 (0.90)

*Leaves sampled in December and litter in February.

Table 5.11: Phosphorus concentrations of fuel load and ash from different vegetation cover types in northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(mg g^{-1})									
Grass	0.7 (0.30)	0.2 (0.02)	0.7 (0.10)	0.8 (0.07)	0.4 (0.10)	0.4 (0.03)	1.7 (0.10)	1.3 (0.10)	0.6 (0.10)	0.4 (0.04)
Leaves/litter	0.5 (0.10)	0.3 (0.40)	0.6 (0.10)	0.6 (0.05)	0.8 (0.10)	0.3 (0.04)	1.1 (0.10)	0.9 (0.06)	0.9 (0.10)	0.5 (0.10)
Twigs	0.5 (0.10)	0.3 (0.04)	0.3 (0.10)	0.5 (0.04)	0.5 (0.10)	0.4 (0.00)	1.0 (0.40)	0.8 (0.05)	0.5 (0.20)	0.5 (0.03)
Fine ash	1.9 (0.20)	0.6 (0.04)	1.7 (0.10)	3.4 (0.30)	1.4 (0.09)	0.5 (0.03)	2.3 (0.40)	2.4 (0.10)	2.1 (0.40)	0.7 (0.10)
Coarse ash	1.6 (0.07)	0.6 (0.04)	0.7 (0.07)	1.2 (0.10)	1.2 (0.06)	0.2 (0.02)	1.8 (0.30)	1.1 (0.10)	2.5 (0.50)	0.6 (0.07)

*Leaves sampled in December and litter in February.

Table 5.12: Potassium concentrations of fuel load and ash from different vegetation cover types in northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(mg g^{-1})									
Grass	2.2 (0.10)	2.4 (0.10)	2.7 (0.10)	1.7 (0.05)	1.6 (0.10)	2.5 (0.10)	3.0 (0.30)	2.2 (0.10)	2.0 (0.10)	1.9 (0.10)
Leaves/litter	1.7 (0.10)	1.8 (0.09)	3.3 (0.20)	1.3 (0.10)	1.3 (0.10)	1.8 (0.09)	2.6 (0.10)	1.5 (0.07)	2.2 (0.10)	1.8 (0.10)
Twigs	1.4 (0.10)	0.9 (0.10)	2.3 (0.10)	1.3 (0.20)	0.7 (0.10)	1.4 (0.50)	1.9 (0.10)	1.3 (0.10)	1.7 (0.10)	1.3 (0.20)
Fine ash	13.0 (1.30)	4.2 (0.20)	11.4 (1.00)	8.6 (0.40)	12.8 (0.80)	4.7 (0.20)	7.9 (1.60)	4.9 (0.20)	5.1 (0.40)	10.5 (1.20)
Coarse ash	9.3 (0.60)	4.4 (0.20)	4.0 (0.40)	4.5 (0.60)	4.5 (0.20)	2.6 (0.20)	3.1 (0.70)	2.9 (0.30)	4.3 (1.20)	7.8 (0.80)

*Leaves sampled in December and litter in February.

Table 5.13: Sodium concentrations of fuel load and ash from different vegetation cover types in northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(mg g^{-1})									
Grass	0.1 (0.01)	0.1 (0.01)	0.3 (0.01)	0.1 (0.01)	0.1 (0.01)	0.1 (0.01)	0.2 (0.01)	0.1 (0.01)	0.2 (0.01)	0.1 (0.01)
Leaves/litter	0.2 (0.01)	0.1 (0.01)	0.4 (0.01)	0.1 (0.01)	0.2 (0.01)	0.1 (0.01)	0.3 (0.01)	0.1 (0.01)	0.3 (0.01)	0.2 (0.02)
Twigs	0.2 (0.01)	0.1 (0.01)	0.4 (0.01)	0.1 (0.02)	0.1 (0.01)	0.1 (0.01)	0.3 (0.01)	0.1 (0.01)	0.3 (0.01)	0.2 (0.01)
Fine ash	0.7 (0.02)	0. 3 (0.01)	0.7 (0.01)	0.2 (0.01)	0.4 (0.01)	0.2 (0.01)	0.5 (0.09)	0.2 (0.01)	0.5 (0.04)	0.2 (0.02)
Coarse ash	0.4 (0.01)	0.3 (0.01)	0. 2 (0.03)	0.2 (0.01)	0.4 (0.01)	0.2 (0.01)	0.3 (0.05)	0.2 (0.01)	0.4 (0.04)	0.2 (0.02)

*Leaves sampled in December and litter in February.

The lowest and highest concentrations of P were measured in the grass component at the shrub and grass/tree savanna sites, respectively (Table 5.11), and ranged from 0.2 to 1.7 mg g^{-1}. The highest concentration of K was recorded in the leaf component and the lowest in the twig component (Table 5.12). Na concentration was much lower in the fuel components as compared to other nutrients, with the highest and lowest values measured in the twig component in both the grass and shrub savanna sites, respectively (Table 5.13). This is probably due to the fact that Na is not a nutrient element essential to plant growth.

The highest Ca concentration measured was 7.2 mg g^{-1} in the leaf component at the grass savanna site and the lowest was 0.2 mg g^{-1} in the litter component at the shrub savanna site (Table 5.14). Mg concentration ranged from 0.2 to 3.4 mg g^{-1}, with the highest concentration in the litter component and the lowest in the grass component (Table 5.15).

In all the three fuel components in the early dry season, leaves had the highest concentrations of N, K, Na, Ca and Mg whereas grass had the lowest N, C, Na, and Ca concentrations. Relatively lower concentrations of P, K, and Mg, were measured in twigs. Similar concentrations were measured in the late dry season samples, in which case the litter component had the highest concentration of N and Na, while concentrations of N and P were lower in the twig component; Mg did not show any pattern. Cook (1994) measured concentrations in grass, leaves and twigs in the savanna, that are in accordance with the range of concentrations in this study.

The N concentrations in the ash were lower than in the fuel. Conversely, concentrations of P, K, Na, Ca, and Mg were higher in ash than in fuel load (Tables 5.10-5.15). Typically, N has a low volatilization temperature, and much of it is lost in a gaseous form after bushfires, hence reducing its concentration in the ash. In contrast, nutrients like P, K, Na, Ca, and Mg have relatively higher temperatures of volatilization, hence are less likely to be lost in a gaseous form but concentrated in the ash component, especially in the fine ash fraction. Concentrations of all nutrients except N were greater in the fine than in the coarse ash fraction; this has to do with the different level of combustion in both fine and coarse ash. Combustion is relatively incomplete in coarse ash as compared to fine ash, resulting in more N in the coarse than in the fine ash, where combustion efficiency is much higher.

Table 5.14: Calcium concentrations of fuel load and ash from different vegetation cover types in northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover types	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(mg g^{-1})									
Grass	3.9 (0.20)	1.3 (0.02)	2.7 (0.30)	3.5 (0.04)	3.0 (0.20)	1.3 (0.05)	1.8 (0.20)	1.9 (0.10)	2.8 (0.10)	1.5 (0.07)
Leaves/litter	3.8 (0.10)	0.2 (0.07)	7.2 (0.40)	3.8 (0.02)	5.4 (0.30)	2.2 (0.10)	5.2 (0.40)	3.4 (0.10)	5.1 (0.30)	2.6 (0.09)
Twigs	4.1 (0.20)	2.4 (0.20)	3.7 (0.70)	4.3 (0.09)	5.5 (0.10)	3.9 (0.20)	5.4 (0.80)	4.3 (0.10)	6.1 (0.10)	3.5 (0.03)
Fine ash	26.4 (4.20)	2.3 (0.10)	7.5 (0.80)	14.2 (1.00)	14.6 (0.30)	3.0 (0.09)	6.5 (0.15)	2.9 (0.10)	14.7 (0.15)	2.8 (0.10)
Coarse ash	6.6 (0.20)	2.9 (0.10)	1.1 (0.06)	13.6 (1.70)	5.0 (0.30)	4.3 (0.50)	10.6 (0.52)	4.2 (0.60)	6.2 (0.20)	3.6 (0.50)

*Leaves sampled in December and litter in February.

Table 5.15: Magnesium concentrations of fuel load and ash from different vegetation cover types in northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover types	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(mg g^{-1})									
Grass	1.8 (0.40)	2.9 (0.06)	0.2 (0.00)	1.6 (0.03)	0.8 (0.10)	0.26 (0.01)	1.2 (0.20)	1.7 (0.10)	2.7 (0.10)	2.2 (0.10)
Leaves/litter	0.7 (0.10)	3.4 (0.10)	0.4 (0.01)	1.7 (0.10)	1.9 (0.40)	0.27 (0.01)	0.21 (0.80)	1.8 (0.04)	3.3 (0.12)	3.0 (0.20)
Twigs	0.8 (0.10)	2.3 (0.30)	0.3 (0.01)	1.1 (0.05)	1.8 (0.40)	0.21 (0.03)	0.8 (0.10)	1.3 (0.09)	2.4 (0.01)	3.0 (0.03)
Fine ash	3.3 (0.40)	4.5 (0.30)	10.0 (0.03)	20.3 (1.00)	6.8 (0.03)	0.29 (0.20)	5.5 (0.10)	2.9 (0.10)	10.2 (0.90)	1.9 (0.20)
Coarse ash	3.7 (0.10)	1.4 (0.04)	1.2 (0.20)	7.0 (0.50)	1.5 (0.03)	1.2 (0.09)	1.1 (0.20)	1.3 (0.05)	2.4 (0.03)	1.4 (0.20)

*Leaves sampled in December and litter in February.

5.5.2 Nutrient stocks prior to bushfire

The total nutrient stocks prior to bushfires and those of the separate components are presented in Tables 5.16-5.21. There was variability among the vegetation cover types in the pre-bushfire N stock in both the early and late dry seasons. The grass/shrub savanna site recorded the highest N mass of 26 kg ha^{-1}, but was not significantly different from the tree savanna type, which recorded the lowest (21 kg ha^{-1}) in the early dry season. However, in the late dry season, the highest N stock (27 kg ha $^{-1}$) was measured in the grass savanna, and this was significantly different from the grass/shrub savanna, (14 kg ha^{-1}) (Table 5.16).

The P, K, Na, Ca, and Mg stocks were variable across the different vegetation cover types and in both seasons. The highest P content prior to bushfires in the early phase of the dry season was observed in the grass/tree savanna and was significantly different from the lowest P content observed in grass/shrub savanna in the late phase of the dry season. Hence, the grass/tree savanna again recorded the highest P value and shrub savanna significantly the lowest (Table 5.17). The K stock was higher in grass and grass/tree savanna for early and late dry season, respectively (Table 5.18) and significantly lower in shrub savanna (early dry season) and grass/shrub savanna (late dry season). Of all nutrients, Na had the lowest stock (Table 5.19); the highest Na stock was in the grass savanna, which was significantly different from shrub savanna, which was the lowest among the sites early in dry season period. A similar trend was observed late in the dry season. The variations in the Ca stock early in the dry season were not significant; however, this was significant in the late dry season (Table 5.20). Mg stock was highest in the tree savanna and significantly lower in the grass savanna in the early dry season; however, late in the dry season, grass savanna recorded the highest Mg stock and grass/shrub savanna had significantly the lowest (Table 5.21).

The variations in fuel load, especially the grass component (Table 5.8), as well as the concentration of the elements in their respective components (Tables 10 and 15) to a large extent determined the total nutrient stock observed for each vegetation cover type and explains the significant differences in nutrient stock across the different vegetation cover sites. Generally, the grass and grass/tree savannas had the highest nutrient stocks,with shrub savanna recording the lowest (Tables 10 and 15). The variability of the nutrient stock among the vegetation cover sites parallel the differences in the total fuel load and concentration; this is particularly evident in the stocks of N, P, K, Na and Ca.

5.5.3 Nutrient stocks in ash

The nutrient stock remaining in the ash after bushfire for both early and late dry season fire experiments are presented in Tables 5.16 to 5.21. These nutrient stocks varied across the different vegetation cover types and for individual nutrients. Remaining ash contained < 15% of N (Table 5.16), but contained between 17–78 % of P, K, Na, Ca and Mg (Tables 5.16-5.21). Laclau et al. (2002) reported variable figures of some nutrient stocks remaining in the ash after fire, without separation into fine and coarse fractions: the mean values of N and P were higher, while those of K and Ca were much lower than in the present study. Physical factors such as temperature of fire and wind speed could be responsible for differences in nutrient stock after fire, because these factors to a large extent affect the combustion of the fuel load. Higher temperatures measured on the experimental plots favored the massive transport of N, which is known to have a lower volatilization temperature; this is the main reason why the stocks are smaller in the remaining ash as compared to the other nutrients (P, K, Na, Ca and Mg). The export of the nutrients by wind could affect spatial distribution, hence the variability across vegetation cover types.

Table 5.16: Total nitrogen prior to burning, remaining in ash and subsequent losses from different vegetation covers types in savanna of northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna		Sig. Level	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
Mass of nitrogen in fuel load (kg ha $^{-1}$)												
Grass	13.34	6.65	22.99	19.95	22.22	8.26	19.46	16.96	15.49	9.51		
	(1.18)	(0.48)	(1.38)	(1.26)	(2.53)	(0.72)	(1.82)	(2.14)	(1.34)	(0.98)		
Leaves/litter	5.62	8.15	0.86	6.17	1.96	5.98	4.51	7.29	3.18	5.5		
	(1.25)	(1.10)	(0.15)	(0.48)	(0.28)	(0.94)	(1.01)	(2.06)	(0.71)	(0.67)		
Twigs	4.56	1.62	1.42	0.77	2.07	0.32	2.62	1.49	2.81	2.43		
	(0.89)	(0.39)	(0.29)	(0.11)	(0.66)	(0.07)	(0.60)	(0.40)	(0.81)	(0.39)		
Total	23	16^{c}	25	27^{a}	26	14^{c}	27	26^{ab}	21	17^{bc}	NS	<0.01
	(2.09)	(1.56)	(1.42)	(1.12)	(2.24)	(1.00)	(1.68)	(2.27)	(2.26)	(1.14)		
Mass of nitrogen in ash (kg ha $^{-1}$)												
Fine ash (<1mm)	0.57	0.90	0.94	1.86	0.35	0.75	0.56	1.63	0.53	0.92		
	(0.04)	(0.16)	(0.13)	(0.25)	(0.02)	(0.09)	(0.07)	(0.26)	(0.09)	(0.22)		
Coarse ash (>1mm)	0.78	0.67	1.19	0.67	1.75	0.69	1.44	2.16	1.1	1.12		
	(0.10)	(0.13)	(0.19)	(0.10)	(0.19)	(0.12)	(0.23)	(0.42)	(0.08)	(0.28)		
Total	1.34	1.72	2.1	2.50	2.1	1.43	1.71	3.78	1.60	1.92		
	(0.14)	(0.20)	(0.31)	(0.30)	(0.21)	(0.17)	(0.24)	(0.58)	(0.14)	(0.21)		
Loss of nitrogen (kg ha $^{-1}$)												
Losses	22	14.6^{b}	23	24^{a}	24	13^{b}	25	22^{a}	20	15^{ab}	NS	<0.01
	(2.11)	(1.65)	(1.56)	(1.28)	(2.36)	(1.01)	(1.56)	(2.43)	(2.21)	(1.33)		
Relative loss of nitrogen (%)												
% Losses	96	90	92	90	92	90	93	85	93	88		

NS= Non-significant. Values with different superscripted capital and small letters denote significant difference in total nutrient fluxes across the vegetation cover types prior to and after burning for December and February respectively.

Table: 5.17: Total phosphorus prior to burning, remaining in ash and subsequent losses from different vegetation cover types in the savanna of northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna		Sig. Level	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
Mass of phosphorus in fuel load (kg ha $^{-1}$)												
Grass	1.94	0.34	4.25	4.32	2.13	0.62	8.41	6.52	2.91	1.06		
	(1.02)	(0.03)	(1.40)	(0.48)	(0.73)	(0.08)	(0.78)	(0.97)	(0.44)	(0.18)		
Leaves/litter	0.31	0.44	0.06	1.25	0.24	0.36	0.59	1..32	0.35	0.59		
	(0.09)	(0.07)	(0.01)	(0.14)	(0.06)	(0.05)	(0.13)	(0.29)	(0.06)	(0.18)		
Twigs	0.53	0.08	0.09	0.10	0.23	0.03	0.05	0.42	0.36	0.20		
	(0.14)	(0.02)	(0.03)	(0.01)	(0.05)	(0.005)	(0.08)	(0.11)	(0.07)	(0.02)		
Total	2.77^{B}	0.85^{c}	4.39^{B}	6.00^{b}	2.61^{B}	1.02^{c}	9.46^{A}	8.00^{a}	3.52^{B}	2.00^{c}	<0.001	<0.01
	(0.98)	(0.09)	(1.41)	(0.50)	(0.75)	(0.06)	(0.79)	(1.16)	(0.44)	(0.15)		
Mass of phosphorus in ash (kg ha $^{-1}$)												
Fine ash	0.67	0.37	1.23	2.08	0.32	0.38	0.62	2.23	1.14	0.47		
(<1mm)	(0.09)	(0.04)	(0.16)	(0.36)	(0.02)	(0.02)	(0.17)	(0.27)	(0.22)	(0.13)		
Coarse ash	0.19	0.19	0.35	0.23	0.35	0.11	0.49	0.47	0.24	0.25		
(>1mm)	(0.02)	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.09)	(0.11)	(0.13)	(0.09)		
Total	0.85	0.57	1.58	2.31	0.67	0.49	1.41	2.68	1.38	0.69		
	(0.11)	(0.06)	(0.16)	(0.38)	(0.03)	(0.04)	(0.20)	(0.37)	(0.20)	(0.05)		
Loss of phosphorus (kg ha $^{-1}$)												
Losses	1.9^{B}	0.29^{c}	2.8^{B}	3.31^{ab}	1.9^{B}	0.53^{c}	8.3^{A}	5.57^{a}	2.3^{B}	1.09^{bc}	<0.001	<0.01
	(0.95)	(0.10)	(1.35)	(0.56)	(0.76)	(0.07)	(0.78)	(1.08)	(0.42)	(0.17)		
Relative loss of phosphorus (%)												
% Losses	69	34	64	59	74	52	88	67	63	60		

NS= Non-significant. Values with different superscripted capital and small letters denote significant difference in total nutrient fluxes across the vegetation cover types prior to and after burning for December and February respectively.

Table 5.18: Total potassium prior to burning, remaining in ash, and subsequent losses from five sites in the savanna of northern Ghana (December 2002 and February 2003). Values are mean, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna		Sig. Level	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
Mass of potassium in fuel load (kg ha $^{-1}$)												
Grass	7.09	3.74	16.84	9.74	7.92	4.17	14.76	11.40	9.96	4.51		
	(0.72)	(0.27)	(1.16)	(0.63)	(0.93)	(0.34)	(1.70)	(1.59)	(1.21)	(0.65)		
Leaves/Litter	1.27	2.66	0.39	2.64	0.39	1.97	1.37	2.12	0.93	2.06		
	(0.30)	(0.35)	(0.09)	(0.32)	(0.06)	(0.29)	(0.27)	(0.40)	(0.14)	(0.39)		
Twigs	1.43	0.30	0.49	0.26	0.37	0.10	1.23	0.61	0.91	0.59		
	(0.35)	(0.10)	(0.08)	(0.06)	(0.09)	(0.05)	(0.18)	(0.13)	(0.21)	(0.06)		
Total	9.8^{B}	6.7^{c}	17.7^{A}	12.6^{ab}	8.7^{B}	6.2^{c}	17.5^{A}	14.0^{a}	11.8^{B}	7.0^{bc}	<0.001	<0.01
	(1.08)	(0.55)	(1.89)	(0.88)	(0.87)	(0.33)	(1.76)	(1.85)	(1.41)	(0.82)		
Mass of potassium in ash (kg ha $^{-1}$)												
Fine ash	4.37	2.58	8.21	4.94	3.02	3.63	2.15	4.52	6.19	3.36		
(<1mm)	(0.43)	(0.29)	(0.98)	(0.61)	(0.22)	(0.21)	(0.63)	(0.60)	(0.64)	(0.86)		
Coarse ash	1.00	1.39	1.97	0.79	1.29	0.95	0.83	1.24	2.01	1.87		
(>1mm)	(0.11)	(0.22)	(0.21)	(0.11)	(0.17)	(0.18)	(0.17)	(0.28)	(0.17)	(1.05)		
Total	5.37	3.97	10.17	5.7	4.3	4.58	2.98	5.75	8.20	5.23		
	(0.43)	(0.48)	(1.22)	(0.69)	(0.20)	(0.27)	(0.75)	(0.87)	(0.68)	(0.74)		
Loss of potassium (kg ha^{-1})												
Losses	4.4^{B}	2.60^{bc}	7.5^{B}	6.77^{ab}	4.4^{B}	1.58^{c}	14.4^{A}	8.40^{a}	3.6^{B}	1.78^{bc}	<0.001	<0.01
	(0.81)	(0.7)	(1.33)	(1.25)	(0.89)	(0.40)	(1.19)	(1.94)	(1.02)	(0.68)		
Relative loss of potassium (%)												
% Losses	45	40	42	54	51	26	83	59	31	25		

NS= Non-significant. Values with different superscripted capital and small letters denote significant difference in total nutrient fluxes across the vegetation cover types prior to and after burning for December and February respectively.

5.5.4 Nutrient losses through volatilization and ash transport

Nutrient stocks are affected by fire events in three ways: they can decrease due to volatilization or particle transport, be transformed from organic to inorganic form in ash or remain on site in the form of residual, uncombusted debris. The fates of nutrient stocks during bushfire events generally are influenced by the volatilization temperature of the respective nutrient.

Nutrients released during combustion are transferred into the atmosphere and transported over long distances in smoke plumes and thus lost to the immediate environs (Evans and Allen, 1971; Smith and Bowes, 1974; Raison, 1979; Mackensen, 1996). Air currents and updrafts during fire carry particles of ash that remove other nutrients from the site. Bird and Cali (1998) reported that the products of modern biomass burning in sub-Saharan Africa have been detected as far west as Barbados.

Relating the total nutrient stocks before burning and what remains in the ash (Tables 5. 16 - 5.21) indicates nutrient losses. The observed differences and the subsequent total atmospheric transfer of nutrients results from volatilization and particulate (ash) movement. The relative contribution of volatilization as compared to particulate mechanisms of elemental transfer depends largely on the volatilization temperature of the element being considered and on fire intensity, which affects both temperatures generated and the amount of ash removed in the convection column.

Nitrogen is volatilized at low temperatures ($T < 400^{o}C$; Lide, 1998). Temperatures above 400 ^{o}C to a high of 520^{o}C were observed in the bushfires across the different vegetation cover types, which explain the massive atmospheric transfer of N (Table 5.16) in both early and late dry season fires. Losses of N were 20 to 25 kg ha^{-1} early in the dry season and 13 – 24 kg ha^{-1} late in the season; these represent 92 – 96 % and 85 – 90 %, respectively (Table 5.16). Clearly, N loss was higher in grass/tree and grass savanna in both seasons as compared to the other vegetation cover types. This was influenced by the quality and quantity of fuel loads in these vegetation cover types. These sites were characterized by a high fuel load, mainly herbaceous and easily combustible, thus enhancing fire intensity, which increases the quality of burn. In contrast the shrub and tree savanna sites comprise more woody vegetation with a discontinuous herbaceous stratum, hence a lower fuel load and quality of burn.

Phosphorus loss was quite variable: 34 – 88 % of the total pre-bushfire stocks were lost during bushfire (0.29– 8.3 kg ha^{-1}). Potassium loss was less than 60 % across the vegetation cover types except in the grass/tree savanna, where it was 83 % (Table 5.18). Losses of Na, Mg and Ca were much higher than expected. These ranged from 26 – 82 % of the total pre-bushfire stock (Table 5.19-5.21) across vegetation types and season. Considering the volatilization temperatures of P (T= 774 ^{o}C, sublimation temperature of P_4O_{10} = 360 ^{o}C), K (T = 774 ^{o}C), Mg (T =1104 ^{o}C) and Ca (T = 1484^{o}C) (see Weast, 1980), the high exports of the nutrients (K, Na, Mg and Ca) must be largely due to ash transport, since non-particulate losses for these nutrients are unlikely.

Phosphorus is likely to be volatilized from burning plant materials as P_4O_{10} (commonly referred to phosphorus pentoxide, P_2O_5). This is the only product of burning P when oxygen is in excess, but volatile P_2O_6 is formed when oxygen is limiting (Cotton and Wilkinson, 1962). Gaseous losses of Ca are less likely, because a major proportion of it is in the structural components of cell walls in inorganic form (Christiansen and Foy, 1979), which has a high volatilization temperature of 1484^{o}C.

The ash, especially the fine ash, contained high concentrations of cations (especially K, Ca, Na and Mg) and P (Tables 5.11– 5.15). Compared to the fuel load, concentrations of P, K, Na, Ca, and Mg in ash were several times higher. Fine ash, which is more mineral in nature, contains much higher nutrient concentrations (P, K, Ca, Na and Mg) than coarse ash, and the nutrient-rich fine ash is very light and thus susceptible to transport from a site either in smoke, or subsequently, via the action of wind.

Table 5.19: Total sodium prior to burning, remaining in ash, and subsequent losses from different vegetation covers in the savanna of northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna		Sig. Level	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
Mass of sodium in fuel load (kg ha $^{-1}$)												
Grass	0.32	0.13	1.73	0.60	0.59	0.14	0.89	0.28	0.79	0.25		
	(0.04)	(0.01)	(0.10)	(0.07)	(0.16)	(0.02)	(0.10)	(0.04)	(0.09)	(0.03)		
Leaves/litter	0.10	0.18	0.05	0.24	0.04	0.07	0.17	0.11	0.18	0.17		
	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)		
Twigs	0.16	0.03	0.09	0.03	0.03	0.01	0.14	0.04	0.15	0.07		
	(0.04)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.03)	(0.01)		
Total	0.58^{C}	0.34^{b}	1.87^{A}	0.86^{a}	0.66^{C}	0.24^{b}	1.20^{B}	0.44^{b}	1.10^{BC}	0.48^{b}	<0.001	<0.01
	(0.08)	(0.03)	(0.10)	(0.09)	(0.16)	(0.02)	(0.13)	(0.06)	(0.12)	(0.04)		
Mass of sodium in ash (kg ha $^{-1}$)												
Fine ash	0.22	0.15	0.50	0.12	0.09	0.10	0.14	0.11	0.28	0.09		
(<1mm)	(0.01)	(0.01)	(0.03)	(0.01)	(0.01)	(0.01)	(0.03)	(0.02)	(0.02)	(0.01)		
Coarse ash	0.05	0.08	0.10	0.04	0.09	0.04	0.08	0.06	0.11	0.06		
(>1mm)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.03	(0.01)	(0.01)		
Total	0.26	0.23	0.60	0.17	0.18	0.14	0.23	0.17	0.38	0.13		
	(0.01)	(0.02)	(0.05)	(0.01)	(0.01)	(0.02)	(0.04)	(0.04)	(0.01)	(0.01)		
Loss of sodium (kg ha^{-1})												
Losses	0.35^{C}	0.11^{b}	1.3^{A}	0.70^{a}	0.48^{BC}	0.10^{b}	0.98^{AB}	0.27^{b}	0.67^{BC}	0.33^{b}	<0.001	<0.01
	(0.07)	(0.04)	(0.12)	(0.09)	(0.17)	(0.02)	(0.14)	(0.05)	(0.13)	(0.12)		
Relative loss of sodium (%)												
% Loss	56	32	68	81	73	41	82	61	63	69		

NS= Non-significant. Values with different superscripted capital and small letters denote significant difference in total nutrient fluxes across the different vegetation cover prior to and after burning for December and February respectively.

Table 5.20: Total calcium prior to burning, remaining in ash, and subsequent losses from different vegetation cover types in the savanna of northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna		Sig. Level	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
Mass of calcium in fuel load (kg ha $^{-1}$)												
Grass	12.70	2.01	16.89	20.18	15.58	2.11	9.16	9.99	13.23	3.46		
	(1.33)	(0.14)	(2.49)	(1.10)	(1.87)	(0.15)	(1.43)	(1.48)	(1.13)	(0..31)		
Leaves/litter	2.72	3.32	0.79	7.58	1.53	2.55	2.80	5.12	2.17	2.81		
	(0. 55)	(0. 39)	(0.16)	(0. 56)	(0.18)	(0.42)	(0. 58)	(0. 96)	(0.44)	(0. 34)		
Twigs	4.07	0.69	1.06	0.69	3.07	0.2	3.67	2.39	3.67	1.61		
	(0. 91)	(0.19)	(0. 35)	(0.15)	(0. 92)	(0.07)	(0.74)	(0.7)	(1.07)	(0.31)		
Total	19.49	6.0^{c}	18.7	28.0^{a}	20.2	5.0^{c}	15.6	18.0^{b}	19.1	8.0^{c}	NS	<0.01
	(2. 20)	(0. 54)	(2.40)	(1.47)	(2. 29)	(0. 36)	(2. 24)	(2. 35)	(1. 99)	(0.74)		
Mass of calcium in ash (kg ha $^{-1}$)												
Fine ash	8.77	1.79	5.21	8.18	3.46	2.24	1.73	2.62	7.15	1.67		
(<1mm)	(1.38)	(0.21)	(0.45)	(1.00)	(0.19)	(0.17)	(0.56)	(0.27)	(1.34)	(0.31)		
Coarse ash	0.78	0.99	0.57	2.74	1.40	1.39	2.33	2.10	1.05	1.29		
(>1mm)	(0.12)	(0.18)	(0.05)	(0.66)	(0.13)	(0.36)	(0.67)	(0.81)	(0.09)	(0. 33)		
Total	9.54	2.78	5.77	10.91	4.86	3.63	4.0	4.71	8.27	2.76		
	(1. 33)	(0. 37)	(0.48)	(1. 32)	(0. 26)	(0.49)	(0.89)	(1.06)	(1. 37)	(0.07)		
Loss of calcium (kg ha^{-1})												
Losses	9.9	2.96^{d}	12.9	17.26^{a}	15.3	1.61^{d}	11.6	12.80^{ac}	10.9	4.54^{cd}	NS	<0.01
	(2.56)	(0.65)	(2.46)	(2.16)	(2.38)	(0.44)	(2.11)	(1.80)	(2. 57)	(1. 91)		
Relative loss of calcium (%)												
% Loss	51	52	69	61	76	31	74	71	57	60		

NS= Non-significant. Values with different superscripted capital and small letters denote significant difference in total nutrient flux across the different vegetation cover types prior to and after burning for December and February respectively

Table 5.21: Total magnesium prior to burning, remaining in ash, and subsequent losses from different vegetation cover types in the savanna of northern Ghana (December 2002 and February 2003). Values are means, standard errors in parenthesis

Vegetation cover	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna		Sig. Level	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
Mass of magnesium in fuel load (kg ha $^{-1}$)												
Grass	6.03	4.53	1.45	8.95	3.93	4.47	6.36	8.60	13.34	5.26		
	(1.78)	(0.27)	(0.07)	(0.54)	(0.45)	(0.50)	(1.91)	(1.01)	(1.09)	(0.69)		
Leaves/litter	0.42	5.12	0.05	3.30	0.5	3.07	1.01	2.55	1.14	3.26		
	(0.11)	(0.69)	(0.01)	(0.35)	(0.08)	(0.51)	(0.32)	(0.36)	(0.32)	(0.25)		
Twigs	0.72	0.65	0.06	0.18	1.48	0.14	0.51	0.69	1.49	1.36		
	(0.29)	(0.20)	(0.01)	(0.03)	(0.75)	(0.05)	(0.09)	(0.17)	(0.41)	(0.24)		
Total	7.18^{B}	10.0^{ab}	1.56^{C}	12.36^{a}	6.0^{B}	8.00^{b}	7.9^{B}	12.00^{a}	15.97^{A}	10.00^{ab}	<0.001	<0.02
	(1.89)	(0.90)	(0.08)	(0.77)	(0.98)	(0.54)	(1.2)	(1.08)	(1.44)	(0.83)		
Mass of magnesium in ash (kg ha $^{-1}$)												
Fine ash	1.12	2.66	0.62	7.77	1.59	2.25	1.52	2.70	6.16	1.42		
(<1mm)	(0.15)	(0.27)	(0.05)	(1.39)	(0.08)	(0.19)	(0.40)	(0.29)	(0.64)	(0.33)		
Coarse ash	0.43	0.49	0.44	1.40	0.42	0.43	0.28	0.55	0.62	0.58		
(>1mm)	(0.06)	(0.08)	(0.11)	(0.27)	(0.04)	(0.06)	(0.05)	(0.11)	(0.07)	(0.27)		
Total	1.5	3.14	1.12	9.18	2.0	2.67	2.2	3.24	6.78	1.98		
	(0.19)	(0.33)	(0.13)	(1.56)	(0.27)	(0.24)	(0.42)	(0.39)	(0.67)	(0.08)		
Loss of magnesium (kg ha $^{-1}$)												
Losses	5.6	6.90^{ab}	0.5	3.20^{b}	4.2	4.89^{ab}	6.1	8.60^{a}	9.2	7.73^{ab}	NS	<0.01
	(1.91)	(1.01)	(0.17)	(0.98)	(0.99)	(0.60)	(1.88)	(1.18)	(1.79)	(0.95)		
Relative loss of magnesium (%)												
% Loss	78	69	32	26	68	65	77	73	57	79		

NS= Non-significant. Values with different superscripted capital and small letters denote significant difference in total nutrient fluxes across the different vegetation cover types prior to and after burning for December and February respectively.

The relative losses of nutrients observed in this study correspond with those in similar savanna environments elsewhere. Hernandez and Lopez (2002) reported losses of 97 % N, 61% P, 76% K, and 65% for both Ca and Mg. These values agree with those obtained in this study. In the East African savanna systems, losses of nutrients by volatilization were 93% N, 32% P, 60% K, 42% Ca, and 12% Mg (Van de Vijver 1999), transfer of N and K were of the order measured in this study, whereas much higher values were recorded for P, Mg and Ca. Cook (1994) measured nutrient losses in the savannas and these are within the mean values in this study. Transfers of nutrients to the atmosphere during the annual burning in the savanna of Congo amounted to 85%, 25%, 39%, 21% and 28% of N, P, K, Ca and Mg, respectively, accumulated in the aerial biomass and litter component prior to bushfire. Losses during bushfires were small for P, K, Ca and Mg compared to the available reserves, but high for N (Laclau et al. 2002). Isichei and Sanford (1980) reported 12 to 15 kg ha^{-1} N loss through biomass burning from grassland ecosystems in savanna locations in western Nigeria. Robertson and Rosswall (1986) estimated that fire accounts for the bulk (about 87%) of all N lost in West Africa.

The interpretation of the significance of site losses of P is important. This is so because soils in the study area have been rated P deficient (Landon, 1990) and are inherently low in available P (Abekoe and Tiessen, 1998). It is suggested by Raison et al. (1985a), that detrimental effects on the N-supplying capacity of the soil are likely to be manifested before those of P, because of the relatively large amounts of N lost to the atmosphere.

Element transfer to the atmosphere in this study was broadly comparable to results from ecosystems other than savanna (Sommer, 2000; Mackensen, 1996; Trabaud, 1994; Kauffman, 1993) where fires are more intense and may lead to much higher losses.

5.5.5 Seasonal patterns in nutrient fluxes

Nutrient losses

Generally, nutrient losses were higher in the early dry season bushfires than in the late dry season (Tables 5.16–5.21). Losses of different nutrient stocks were variable in the different vegetation cover types in both seasons. For example, losses of K, Na and Mg in the grass savanna were higher early in the dry season but lower in the late dry season (Tables 5.16, 5.17 and 5.21).

The relative losses of nutrients during bushfires in early and late dry seasons did not show any particular trend. Generally higher losses of N and Na were evident in the early dry season. No particular trend was noticed for P, K, Ca, and Mg. The related differences shown between the early and late dry seasons were due to differences in physical factors like wind speed, humidity and air temperature.

Conditions of lower humidity, higher air temperatures and wind speed (Table 5.9) measured in the late dry season are very favorable for bushfires which start easily. At this time of the year, plant material, especially grasses, is dry and burns easily, and these fires spread very fast due to high wind speed. In cases the where the wind is turbulent, the fire may spread so fast that combustion could be incomplete during this period, leading to mosaic burning and lower combustion efficiency. Conversely, in the early dry season, the plant material is just dry enough to burn and the conditions of low wind and high duration of fire allow comparatively higher combustion. The results suggest that the month of December seems not to be early enough to minimise the destructive nature of bushfires, as comparatively higher losses of nutrients were observed during the December bushfires in most cases (Tables 5.16 - 5.21).

November might be a better month for early burning, as opposed to the December burning practised by the inhabitants of the study area. Currently, there are few unstructured bushfires in November. During November, the rains have just ended, the dry season is beginning to set in and the effect of the harmattan is absent. Bushfires during this period are usually patchy and small in spatial extent (due to high moisture content of fuel). Later in the season, for instance in December to February, bushfires increase in size and intensity as grasses get cured. If the burning season begins with small fires, the result is a mosaic landscape, with patches of differing composition and structure. Conversely, if the fire begins late, the ensuing high intensity results in more homogenous landscape bushfires (Laris, 2002).

5.5.6 Nutrient losses and balances

Element transfer into the atmosphere results from volatilization (non-particulate transfer) and particulate (ash) movement. Particulates may be redeposited on the burnt site or adjacent areas either as dry fallout (Evans and Allen, 1971; Smith and Bowes,

1974) or during rainfall (Lewis, 1974). Non-particulate losses are more likely to represent permanent losses from the site.

Of all nutrients, only N is largely transferred to the atmosphere in a gaseous form, and this is due to its low volatilization temperature. However, P is also likely to be lost in a gaseous form. The N and P losses are critical to the ecosystem functioning of this study area, since they are important nutrients for plant growth and are already limiting in the study area (Table 5.1). The other nutrients (K, Na, Mg and Ca) are lost mainly by particulate transfer.

The high loss of N as compared to that of the other nutrients suggests that frequent bushfires may lead to loss of N such that the productivity of the system begins to decrease. This is especially so when the major part of the N pool is found aboveground and returns through N_2–fixation and deposition are low (Turner et al., 1997). Although the amount of N lost from the aboveground nitrogen stock is significant, it is only 1.4 – 3.0 % of the total soil nitrogen stock. But the effects of fire on the cycling fractions of N are more important than effects on the absolute reserves of soil N in the ecosystem (Walker et al., 1986), as these reserves are not readily available to plant communities in the ecosystem.

Permanent losses of nutrients are more likely for those nutrients transferred in gaseous or non-particulate forms (Raison et al., 1985a). However, most of the nutrient loss might be regained by wet and dry deposition, on the assumption that the total nutrient content of the wet and dry deposition are transferred to the soil. Most of the rains in this region are terrestrial in origin, and the bushfires in this region can contribute to some of the nutrient load in rain. In Table 5.22, the net losses of nutrients were calculated by subtracting the mean annual input of nutrients through rainfall in the region (Stoorvogel and Smaling, 1990) from the quantity of nutrients transferred to the atmosphere in gaseous form during bushfires. The values in Table 5.22 show that wet and dry deposition were insufficient to balance the losses for N, P and K in the various vegetation cover types, hence indicating net losses. However, deposition returned P and K to vegetation types that had shrubs as one of their components, but net losses were recorded in the others. Thus, shrub vegetation may be the least susceptible to long-term loss of P resulting from burning.

However, losses of N were comparatively higher. Symbiotic and non-symbiotic biological fixation of N may replace some of the N lost during fires. In a similar environment at Lamto - Ivory Coast in West Africa, non-symbiotic fixation of N by bacteria associated with grasses contributed 12 kg ha^{-1} yr^{-1} of N and consequently restores 60 % of N lost during fires (Balandreau, 1976). Even if it is assumed that this process is relevant in the study area, the entire N loss is not likely to make up for this deficit. This would not confirm the assertion by Frost and Robertson (1987) that N losses through bushfires, in savanna systems do not exceed inputs through atmospheric deposition and fixation. The net losses of N, P and K under annual bushfires in the savannas of northern Ghana are estimated to be approximately 10 – 22 kg ha^{-1}, 1-7 kg ha^{-1} and 2-12 kg ha^{-1}, respectively. The grass and grass/tree cover type recorded the highest net losses. There is a danger that a larger amount of nutrients will be lost in the future, since there is an unfortunate trend in this study area toward the gradual dominance of herbaceous plant material. Annual burning of these savannas could have a serious impact on the losses of N, and consequently on the ecosystem in terms of the soil. Considering the very low N inherent content (< 0.1 %) of the soils, biological fixation of N is necessary to insure the sustainability of the savanna and compensate for the large N losses, through bushfires. Bushfires would have to be reduced in frequency if this is to be successful.

Table 5.22: Net nutrient transfer to the atmosphere as a result of annual bushfires from five sites in the savanna of northern Ghana (December 2002 and February 2003)

Nutrient	N		P		K	
Season	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
	(Kg ha^{-1})					
[1]Deposition	2.85	2.85	0.97	0.97	2.01	2.01
Shrub savanna (SS)						
Loss	22	14.6	1.9	0.29	4.4	2.60
Net transfer	19.15	11.75	0.93	-0.68	2.39	0.59
Grass savanna (GS)						
Loss	23	24	2.8	3.31	7.5	6.77
Net transfer	20.15	21.15	1.83	2.34	5.49	4.76
Grass/shrub savanna (GSS)						
Loss	24	13	1.9	0.53	4.4	1.58
Net transfer	21.15	10.15	0.93	-0.44	2.39	-0.43
Grass/tree savanna (GTS)						
Loss	25	22	8.3	5.57	14.4	8.40
Net transfer	22.15	19.15	7.33	4.6	12.39	6.39
Tree savanna (TS)						
Loss	20	15	2.3	1.09	3.6	1.78
Net transfer	17.15	12.15	1.33	0.12	1.59	-0.23

[1]Recalculated from Stoorvogel and Smaling (1990) for region of uncertain rainfall. Negative values for the net transfer indicate a net gain of nutrients to the different vegetation cover types.

Summary and ecological implication

Total nutrient stock was influenced by the quantity of fuel load present. Vegetation cover types (grass and grass/tree savanna) with a higher fuel load recorded the highest of nutrient stock. In all vegetation cover types, 25- 97 % of all measured macronutrients in the fuel load were transferred to the atmosphere during the fires. Nitrogen, P, and K recorded net losses, N losses being the highest. Losses can be replaced naturally by inputs from rain and, in the case of N, from biological fixation. However, the capacity of such inputs to balance outputs resulting from any particular fire regime will vary greatly between ecosystems.

The input capacity of the ecosystem of northern Ghana was insufficient to balance the outputs. The general seasonal pattern shows that nutrient losses were largely higher in early dry season bushfires than in late dry season.

The nutrient transfer to the atmosphere, be it particulate or volatilization, constitutes site losses and has far-reaching implications for ecosystem functioning. In this study, significant quantities of macronutrients were transferred to the atmosphere during the bushfires, but the study confirmed that most of the N contained in combusted fuel was lost to the atmosphere in gaseous form. Nitrogen losses during fire can be partially replaced naturally by inputs in rain and from biological fixation. The capacity of such inputs to balance outputs resulting from any particular fire regime will vary greatly between ecosystems, but will depend to a large degree on the contribution of leguminous plants and free living bacteria. Biological fixation may be of insufficient magnitude to replace the lost N. Further research is required to confirm this, because reliable estimates of rates of non-symbiotic fixation in this area are scanty, and the possible role of non-symbiotic and other flora is unknown.

This study indicates that, under a regime of annual burning in which the burns are complete, the N reserves of savannas such as those of northern Ghana may be depleted, and this may subsequently lead to the net loss of N, P and K. To reduce the likelihood of progressive land degradation, the contribution of fire to nutrient cycling would need to be reduced. This could be achieved by decreasing the frequency of fires either temporally or spatially, through promoting patchy fires such as can occur much earlier in the dry season period considered in this study.

Prevention of bushfires through mass education should be encouraged. Prophylactic measures such as educating people about the outbreaks and consequences for fires on the environment as a whole would be a step in the right direction.

5.6 Effect of fire on soil properties

The savannas of northern Ghana burn frequently and fire is used as a management tool for land preparation. Fires can result in short- and long-term changes in the properties of savanna soils such as the supply of essential nutrients (e.g., N, P, K. Ca and Mg), to which are essential to the long-term sustainability of savanna soils. Fires dramatically alter nutrient cycling through volatilization, substrate transfer in the form of particulate matter, smoke and ash as well as by inducing nutrient losses through leaching (Grier, 1975; Macadam, 1989; Debano et al., 1998). In a study recently conducted in Indonesia, severe burning was found to have drastic effects on soil texture and mineralogy

(Ketterings et al. 2000). The effects of low, moderate and severe fires on physical and chemical properties have been reported (Sertsu and Sanchez 1978; Ulery and Graham 1993; Ketterings and Bigham, 2000).

The aim of this section is to investigate the effects of bushfire on selected physicochemical parameters of savanna soils, before and after bushfire soil samples were taken from 49 sites and analyzed to ascertain any differences.

The mean and standard error (SE) of selected soil properties are shown in Table 5.23. The pH, total N, exchangeable K and Na, increased after fire, while those of available P, OC, SOM, exchangeable Ca, Mg and cation exchange capacity (CEC) decreased. The respective changes observed for OC, total N, K, Ca, Mg, Na, CEC were significant, but for those remaining soil chemical properties, like available P, OC, pH, were not significant (paired t-test, $P < 0.05$, $n = 49$). The higher concentration of K and Na observed in the soils after fire is due to the higher concentrations in the ash. Concentrations of Mg and Ca were lower, and the reason for this is not well understood. The CEC decreased significantly after fire; this is probably due to aggregation of finer particles promoted by heating (Giovanni et al., 1988). Furthermore, the progressive combustion of the organic matter seems to be the most important factor for the decrease of CEC. The reduction of CEC and the generation of thermal cracks in the soil aggregates could accelerate weathering due to increased surface area and may result in loss of K, Ca and Mg through leaching (Arocena and Opio, 2003). The results suggest that fire can lead to an irreversible breakdown of soil minerals because of its influence on chemical and physical processes (Ulery et al., 1996).

The mean OC in the pre-fire sites was slightly higher than that of the post-fire. The decline in OC after fire is attributable to several processes operating simultaneously:

1. The first and foremost is that the inputs of organic matter to the soil are reduced by burning because of the combustion of aboveground biomass and leaf litter.
2. The other possible reason for the decline of OC in soil after fire may be due to the combustion of soil organic matter during the burning of vegetation. Combustion of soil organic matter begins at 220^{o}C (Giovanni et al., 1990) and temperatures measured in this study were about 500^{o}C.
3. The removal of the vegetation tends to increase the number of wetting and drying cycles in the soil surface, due to higher soil temperature (Savage and Vermeulen,

1983) and less interception of rainfall in the after fire environment (Moyo et al., 1998). This in turn increases the rate of mineralization of organic matter, a process known as Birch (1958) effect.

4. Soil temperatures tend to increase after fire because of greater exposure to sunlight and this is likely to increase microbial activity. Knapp et al. (1998), for example, recorded a 20 – 50% increase in CO_2 flux after burning in grass, with unburnt grass averaging 10µmol CO_2 m^{-2} s^{-1} and burnt grass 15µmol CO_2 m^{-2} s^{-1} at the same site. O` Lear et al. (1996) showed that the rate of decomposition of woody vegetation was greater in burnt sites than unburnt sites. Soil temperatures were greater in burnt grass than unburnt grass and differences in CO_2 flux were attributed to this temperature difference.
5. The decline in OC in soil after fire is because microbes tend to respond favorably to the decomposition of alkaline ash in the post-fire environment (Greenwood, 1968; Knapp et al., 1998). An increase in pH also tends to favor microbial growth (Curtin et al., 1998).

There was no significant increase in post-fire pH (Table 5.23). pH will increase at least temporarily on burnt sites. The increase in pH is beneficial to soils of low pH since it influences the availability of most essential nutrients (Ahlgren and Ahlgren, 1960; Wells et al., 1979). Very high pH, as can occur in post-fire soils, is detrimental. For example, Ulery and Graham (1993) observed that pH > 8 is likely to promote clay illuviation and mineral weathering.

The processes discussed above tend to reduce N in post-fire soils, but, on the contrary, an increase of N at post-fire soils was observed and this is not well understood. However, Giovanni et al. (1990) observed an increase in NH_4^+- N at soil temperatures up to 220^{o}C. There was no significant difference between the pre- and post-fire soil samples with respect to P, but only slight increase after fire; and this could have been promoted by mineralization of P, especially the organic form at higher temperatures. Similar results were obtained in a slash-and–burn experiment in Indonesia (Ketterings and Bigham 2002).

Organic P constitutes the most important source of P, because the sandstone, which is the dominant parent material, in the study area is not a source of soil P (Nye and Stephens 1962).

Table 5.23: Paired t-test results of physicochemical properties of soil before and after burning in northern Ghana (n=49)

Parameter/statistic	Before burning mean ± SE	After burning mean ± SE	t	sig. (2 tailed)
Total N (%)	0.06 ± 0.004	0.09 ± 0.01	-5.71	0.01
OC (%)	0.58 ± 0.03	0.57 ± 0.02	0.39	0.69
SOM (%)	1.01 ± 0.05	0.99 ± 0.04	0.398	0.69
Available P (mg g^{-1}) – Bray- I	0.01 ± 0.001	0.01 ± 0.001	1.010	0.32
Exchangeable K (mg g^{-1})	0.02 ± 0.001	0.04 ± 0.003	-8.19	0.01
Exchangeable Ca (mg g^{-1})	0.48 ± 0.04	0.26 ± 0.03	6.05	0.01
Exchangeable Mg (mg g^{-1})	0.16 ± 0.009	0.10 ± 0.009	8.22	0.01
Exchangeable Na (mg g^{-1})	0.01 ± 0.001	0.02 ± 0.001	-2.30	0.03
CEC ($cmol^+ Kg^{-1}$)	5.41 ± 0.24	3.89 ± 0.25	7.05	0.01
pH ($CaCl_2$)	5.33 ± 0.09	5.40 ± 0.08	-1.39	0.17
Sand (%)	61.18 ± 1.54	63.70 ±1.48	-3.79	0.01
Clay (%)	6.64 ± 2.25	6.34 ± 2.11	1.01	0.32
Silt (%)	32.18 ± 1.35	29.96 ± 1. 29	3.10	0.003

The soils were generally sandy loam and characterized by low clay content and a high sand content, resulting in a poor structure. Sand, the dominant inorganic mineral fraction, accounted for > 60 % of the mineral fragments of the pre- and post-fire soils, whereas that of clay was < 10%.

The results show significant increase in the mean proportion of sand particles in the soil and a significant decrease in silt particles after fire, while that of clay did not significantly differ (Table 5.23). The increase in the sand particle size and the corresponding decrease in clay and silt particle size is likely caused by the fusion of clay and silt particles into sand-sized particles. This trend was similar to what Dyrness and Youngberg (1957) reported; similar results were reported by Sreenivasan and Aurangabadkar (1940). Ulery and Graham (1993) also made similar observations. Heating of soils up to 400^oC in the laboratory significantly reduced clay particle size of chaparral soils from southern California (Duriscoe and Wells, 1982), and vertisols from India (Puri and Asghar, 1940) and Ethiopia (Sertsu and Sanchez, 1978; Ketterings and Bigham 2000).

Summary and ecological implication

The majority of soils sampled before and after burning showed changes in soil chemistry in a manner that increases the tendencies of soils to have high N, K, Na, pH and % sand, but low OC, OM, P, Ca, Mg, CEC, and % clay and silt. While short-term benefits of fires on soils such as increased levels of pH and some available nutrients are ideal, there are concerns about long-term loss in nutrients and impaired productivity (Tiedeman et al., 2000). For instance, the reduction in CEC and the generation of thermal cracks in feldspars could accelerate weathering due to increased surface area and may result in loss of K, Ca and Mg through leaching. The results suggest that the severity of bushfires should be closely monitored to prevent irreversible breakdown of soil minerals, because of their influence on chemical and physical processes and site productivity.

5.7 Post-fire surface albedo and surface temperature

Surface albedo is the fraction of the total incident solar radiation that is reflected by a body or surface. Land surface albedo is a key parameter in the global system. It quantifies the radiometric interface between the land surface and the atmosphere. It influences the climate system and defines the shortwave energy input into the biosphere. Natural and anthropogenic changes in vegetation and land use practices affect the spatial, temporal and spectral distribution of its value.

Surface albedo data have many uses and can be used for classifying soils, monitoring surface soil water content, and assessing spatial variations in the radiation budget of the Earth's surface. Albedo is one of the primary factors influencing ecological, biophysical and plant physiological process as well as local and global climates (Yin, 1998; Tooming 2002). Soil surface albedo may modify soil temperature, which in turn affects soil biophysical processes, such as seed germination, root growth, plant development and biomicrobial activity (Potter et al., 1987; Mathias et al., 2002).

With the onset of the dry season, the vegetative matter is dry and a fire event can burn large fronts of the area, blackening the soil as a result of ash deposits. These surface changes are likely to result in altered energy partitioning (enhanced sensible and latent heat fluxes).

There is limited information on how bushfires may affect albedo and subsequently the energy fluxes in the study area. The data collected from burnt and unburnt plots of the sites were used to examine the albedo shift as a result of the bushfires and its implications.

5.7.1 Bushfire impact on surface albedo

In the savanna of northern Ghana, the most dramatic visual change resulting from bushfires is the consumption of the dry herbaceous vegetation and the resultant bare and blackened surface. There was a significant difference between pre- and post-fire mean albedo values (paired t-test, $p < 0.01$ $n = 49$).

The comparison of pre and post-fire albedo in the different vegetation cover types was investigated and is presented in Table 5.24. Pre-fire albedo was highly variable across the vegetation cover types and ranged between 0.16 and 0.22. The variations are largely due to the varying reflective and absorptive properties of the different vegetation cover types. The highest albedo was in shrub savanna which differed significantly from grass savanna. The pre-fire herbaceous vegetation in the dry season had senesced and was relatively brown and absorptive; in addition, the LAI of the herbaceous vegetation coupled with the tall scattered trees was capable of multiple scattering and absorption of incoming shortwave radiation. Furthermore, the very sparse vegetation in the shrub savanna during the dry season resulted in most of the solar radiation being reflected. In contrast grass savanna had relatively dense dry vegetation and was more absorptive, and this resulted in a significantly lower albedo.

Post-fire surfaces of the sites were black and very absorptive. This had an immediate impact on the surface radiation budget by dramatic decrease in albedo which ranged between 0.06 and 0.08 (> 50% of pre-fire albedo values) in all vegetation cover types sampled (Table 5.24). Furthermore, a post-fire event is characterized by loss of vegetation cover, which subsequently alters the radiation balance, rates of evapotranspiration and carbon flux. The differences in observed decrease in albedo were not significant across the vegetation cover types (Table 5.24), due to similar surface properties as a result of ash deposits.

In the work of Beringer et al. (2003) in a similar savanna environment, albedos were between 0.11- 0.12 for pre - fire sites and were reduced to about half in the post-fire sites within the range 0.06 to 0.07. The pre-fire values in the current study are higher due to differences in the vegetation cover types and phenological state. However, similar albedo values were measured for the post-fire. Scholes and Walker (1993) also reported a halving of albedo in the savanna of Africa to a value of 0.06, which is consistent with the current study. Removing the dead litter layer by fire changed the optical properties of the surface, causing an immediate and dramatic reduction in albedo, which averaged 43% on the burnt sites than on the unburnt sites (Bremer and Ham, 1999). This is similar to the values obtained in the current study.

Table 5.24: Albedo and soil surface temperature parameters for five different sites in the savanna region of northern Ghana (February 2003)

Parameter	Albedo		Soil surface temperature (T^{o}C)	
	Unburnt	Burnt	Unburnt	Burnt
Shrub savanna	0.22 ± 0.01^{A}	0.06 ± 0.01	49.8 ± 2.37	58.0 ± 2.45
Grass savanna	0.16 ± 0.01^{C}	0.08 ± 0.00	46.8 ± 2.20	56.0 ± 1.79
Grass/shrub savanna	0.20± 0.00^{AB}	0.06 ± 0.00	52.8 ± 2.13	57.8 ± 1.07
Grass/tree savanna	0.18 ± 0.01^{BC}	0.07 ± 0.01	51.4 ± 2.46	61.8 ± 3.49
Tree savanna	0.19 ± 0.01^{AB}	0.07 ± 0.01	46.2 ± 0.37	53.6 ± 1.40
Sig. Level	0.00	NS	NS	NS

NS= Non-significant. Values with different superscripted capital letters denote significant difference using Bonferroni mean separation test.

5.7.2 Bushfire effect on soil surface temperature

Seasonal and fire-induced shifts in albedo affect the amount of net solar radiation (net short wave radiation) retained at the surface of the soil. The specific variations emanating from the different vegetation cover types are presented in Table 5.24. The mean pre-fire surface temperature was 46 - 53^{o}C across the different vegetation cover types, with grass/shrub vegetation being the highest but not significantly different from grass savanna, where the lowest soil surface temperature was measured (Table 5.24). However, post-fire mean temperature ranged from 54 - 62 ^{o}C, but did not differ significantly across the vegetation cover types. Pre- and post-bushfires temperatures differed significantly (paired t- test, $p < 0.05$, $n = 5$) and were between 46 ^{o}C (pre-fire) and 62 ^{o}C (post-fire). The significant increase in post-fire soil surface temperature is largely due to the exposure of the surface to direct sun radiation after burning, coupled with lower albedo, which translates into increased sensible heat flux.

Summary and environmental implication

Seasonal and fire-induced shifts in albedo affect the amount of net solar radiation (net short wave radiation) retained at the surface of the soil. The high soil surface temperature observed in post-fire soil is probably due to high net absorbed solar radiation as a result of lower albedo, increasing the sensible heat flux, since evapotranspiration is lower. Increased sensible energy used in surface heating could have significant impacts on local to regional atmospheric circulations and climate. At the local scale, depending on the aerodynamic changes in the savanna vegetation following fire, enhanced sensible fluxes over patches of burnt landscape (in the order of 100 km^2) could produce localised areas of convergence and divergence and associated mesoscale circulation systems (Knowles 1993). Such circulation patterns may lead to an increase in spatially fixed convective cloud development and precipitations following fire until fluxes have returned to pre-bushfire conditions (Beringer et al., 2003). Tapper (1991) and Physick and Tapper (1990) showed that landscape contrasts in albedo on burnt areas and their surroundings in Australia can produce quite strong mesoscale circulation systems. Such circulations are known to be capable of producing intense, spatially fixed cloud convection and precipitation under suitable environmental conditions (Keenan et al., 2000; Beringer et al., 2001b).

5.8 Impact of bushfire on surface energy fluxes and moisture indicators

An accurate representation of the surface energy fluxes and moisture indicators is crucial for estimating atmospheric flows over land surfaces across various temporal and spatial scales. More importantly, variations in the diurnal thermal structure and depth of the atmospheric boundary layer determine to a greater extent the exchange of heat and moisture with the underlying land surfaces. In particular, it has been shown that differences in surface energy fluxes over heterogeneous land surfaces induce mesoscale circulations similar to the sea-land breezes (Fast and McCorde, 1991).

It has further been shown that evapotranspiration from heterogeneous land surfaces constitutes a major source of moisture for the summertime extratropical convective precipitation (Mintz, 1984). Similar studies by Pan (1990) and Dastoor and Krishnamurti (1991) show a strong correlation between soil moisture distribution and precipitation patterns of tropical storms.

Therefore, any processes that cause threshold changes in surface energy fluxes and moisture indicators would have significant impact on the climatic conditions of the region of interest. Bushfires create complex islands in a region with highly variable heat and moisture distribution. The resulting heat and moisture gradients induce local to regional mesoscale circulations and complex feedbacks and hence affect the climatic conditions on the regional scale. Therefore, a deeper understanding of bushfire-induced changes in energy fluxes and moisture indicators, which often have threshold changes, is crucial for assessing the impact of regional climate change.

To this end, an experiment was set up to investigate, in particular, threshold changes in the energy and hydrological dynamics induced by bushfire. This section provides some insight into the complex impact of bushfire-induced land use change on diurnal and weekly temporal scales. It constitutes a significant step towards the understanding of such impacts. This section focuses on Bowen ratio and evaporative fraction as moisture indicators because they give better diurnal representation of energy partitioning of the available surface energy into sensible and latent heat fluxes (Bastiaanssen, 1995). For the surface energy balance, the available energy and latent and sensible heat fluxes are investigated. Additionally, the net absorbed solar radiation is modeled, as it is significantly affected by changes in albedo.

To investigate the hypothesis that bushfire causes threshold changes in surface energy fluxes and moisture indicators, a combination of observational and modeling approach was adopted. The BATS scheme (Dickinson et al., 1993) was selected for the exercise because of its suitability for the study. In particular, the input requirements are easy to obtain from literature and measurements.

5.8.1 Diurnal simulations of energy fluxes of burnt and unburnt plots

Bushfire-induced land use change creates complex feedback mechanisms in the ecological dynamics of ecosystems. In particular, most of these feedback mechanisms result from threshold energy changes and hence may further result in irreversible changes. The complexity of the problem requires a combination of measurement and numerical experimentation to enable adequate investigation of the processes at play. This section gives the analysis of the results obtained from such a study. The analysis focuses on the key changes in surface properties resulting from bushfire that has direct effects on land-surface processes on a diurnal temporal scale.

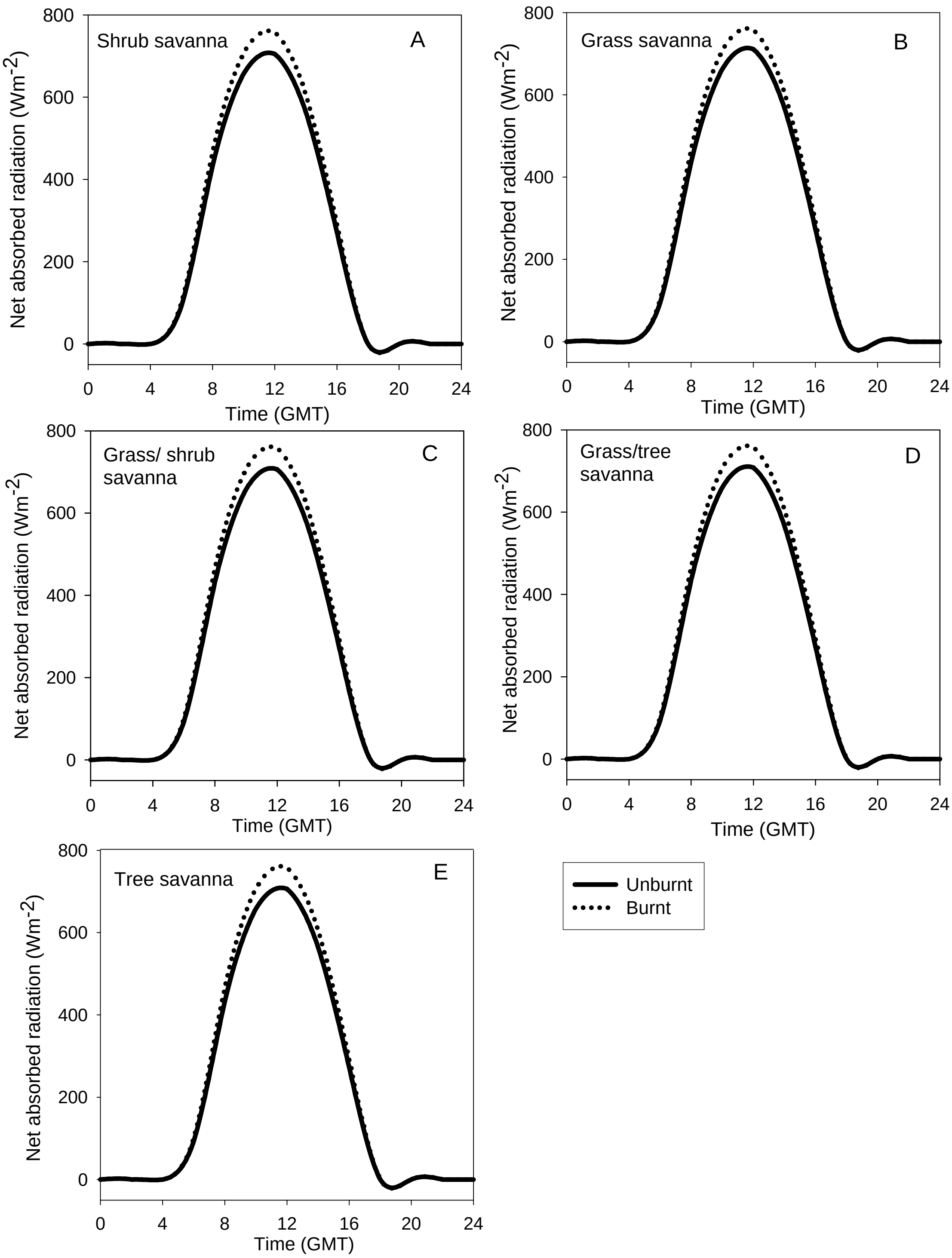
Net absorbed solar radiation

Figures 5.10A-5.10E show the respective graphs for the diurnal variations of the net solar absorbed radiation for the experimental sites (vegetation cover types). The maximum occurs around noon and is given in Table 5.25 for the respective vegetation cover types. The net solar absorbed radiation was similar across the cover types for the burnt condition (758 Wm^{-2}). However, the model response was different for the unburnt case with values ranging from 705 – 711 Wm^{-2}. Comparisons between the burnt and unburnt graphs show differences across the vegetation cover types. The differences represent an increase of 6.6 – 7.5 % (47 - 53 Wm^{-2}, residual) from unburnt to burnt. The trend shows a consistent increase of net absorbed radiation that peaks around 1200 GMT and then declines for both the burnt and unburnt for the respective sites (vegetation cover types). The graphs consistently show that the burnt savanna causes threshold increases in the net absorbed solar radiation. This is due to the fact that reduction in albedo associated with the burning results in increased absorption of solar radiation. Also, for the burnt savanna, the net absorbed solar radiation does not differ significantly across the experimental sites. This can be explained by the fact that the albedo for the burnt sites does not differ enough to cause appreciable differences in the net solar absorbed radiation.

The implications of the increased net solar absorbed radiation is that there would be an increase in daily maximum and a decrease in daily minimum temperatures, as most of the absorbed energy is translated into heating the earth's surface due to the arid harmattan conditions. More importantly, this has serious implications for the functioning of the ecosystem, as increased maximum and decreased minimum diurnal temperatures may alter the equilibrium of ecosystem processes.

Table 5.25: Maximum simulation values of surface energy parameters in the savanna of northern Ghana (February 2003). Calculated using the BATS model (Dickinson et al., 1993).

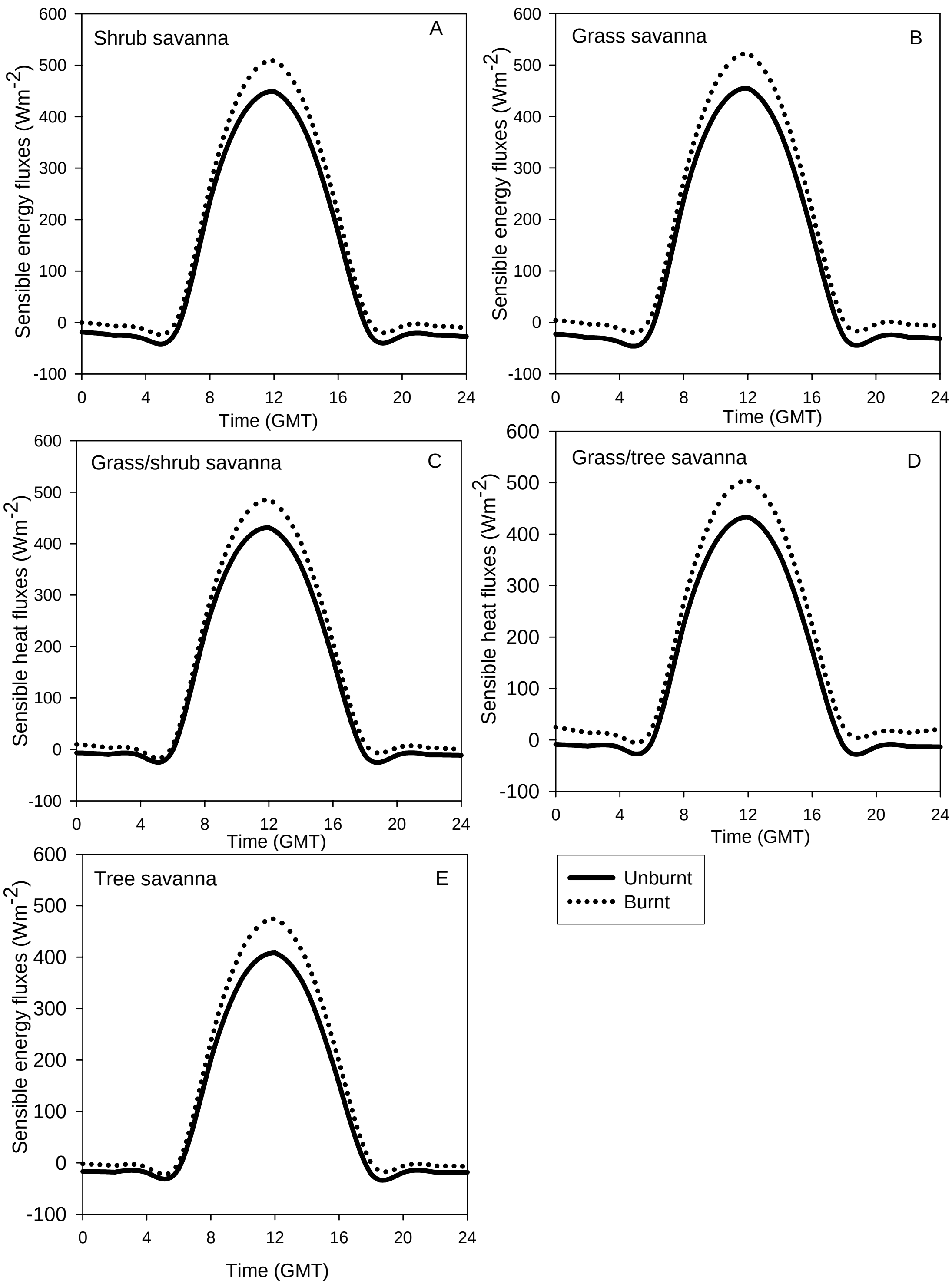
Parameter	Net absorbed radiation (Wm^{-2})	Sensible heat (Wm^{-2})	Latent heat (Wm^{-2})	Bowen ratio (-)	Evaporative fraction (-)
			Shrub savanna		
Unburnt	705	449	57.2	12.68	0.6095
Burnt	758	509	4.54 E-04	1325520.8	7.00 E-05
			Grass savanna		
Unburnt	711	455	57.3	12.50	0.5593
Burnt	758	522	3.84 E-04	1359375	1.50E-04
			Grass/shrub vegetation		
Unburnt	706	431	62.9	12.39	1.07
Burnt	758	485	3.85 E-04	1259740	7.18 E-04
			Grass/tree savanna		
Unburnt	708	433	63.1	12.15	0.8126
Burnt	758	504	4.98 E-04	1012048	5.16E-05
			Tree savanna		
Unburnt	706	408	64.2	9.94	0.6932
Burnt	758	474	3.85 E-04	1231169	7.85 E-07



Figures 5.10A-5.10E: Comparison of diurnal simulations of net absorbed radiation between burnt and unburnt savanna of northern Ghana (February 2003)

Sensible heat fluxes

Figures 5.11A-5.11E show the diurnal variations in sensible heat fluxes for the respective experimental sites. Table 5.25 gives the corresponding diurnal maximum sensible heat fluxes, which occur around noon. The sensible heat fluxes follow a similar trend to that of the net absorbed solar radiation. However, unlike the net absorbed solar radiation, the sensible heat fluxes show marked differences across the vegetation cover types for both the burnt and unburnt savanna. The sensible heat fluxes for the unburnt graphs of the different vegetation cover types ranged from 408 - 455 Wm^{-2} and that of the burnt plots were from 474 to 522 Wm^{-2}. Comparison between the burnt and unburnt plots of the different vegetation covers indicates a significant increase in sensible energy, representing an increase of 12.5 – 16.4 % (54 – 71 Wm^{-2} residual). This suggests that the sensible heat flux is more sensitive to bushfire-induced changes in land surface properties than the net absorbed solar radiation under the given experimental conditions. This can be explained by the fact that bushfire drastically reduces albedo, leading to increased net absorbed solar radiation. Additionally, the associated absence of vegetation subsequently reduces transpiration to a minimum, resulting in the majority of the energy dissipated as sensible heat flux.



Figures 5.11A- 5.11E: Comparison of diurnal simulations of sensible energy fluxes between burnt and unburnt savanna of northern Ghana (February 2003)

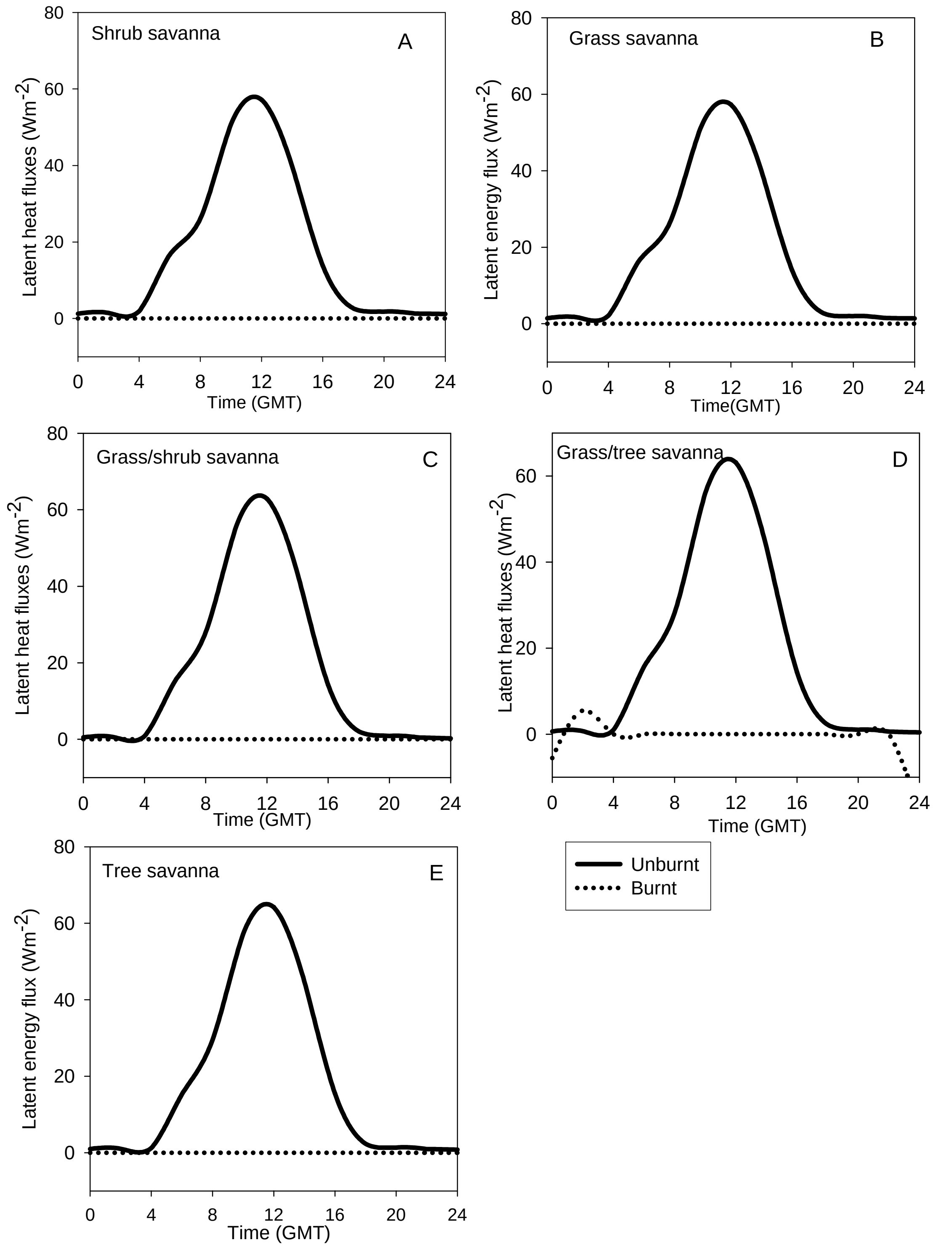
Latent heat fluxes

The plots for the diurnal variation of the latent heat fluxes for the respective experimental sites are shown in Figures 5.12A- 5.12E. The corresponding maximum values around noon are given in Table 5.25. The graphs show drastic changes between the burnt and unburnt savanna compared to those of the net absorbed solar radiation and the sensible heat fluxes. The latent energy of the unburnt parts of the different vegetation covers ranged between 57.2 and 63.1 Wm^{-2}, but that of the burnt vegetation was so low that it could be assumed to be zero (~ 10^{-3} Wm^{-2}). These low values are evidenced in the moisture indicators with very high Bowen ratios and very low evaporative fraction (10^{-5}; discussed in detail in the next section). This suggests an increase in latent heat in excess of over 100%. More importantly, it indicates that the latent heat flux is extremely sensitive to bushfire under the arid harmattan conditions.

These observations can be explained by the fact that the only available moisture for latent heat (transpiration) under the harmattan conditions is the root zone soil moisture, and hence only vegetative surfaces can access the available soil moisture. Therefore, for the burnt case, the latent heat flux is zero, whereas the vegetated surfaces of the unburnt savanna have appreciable values of latent heat fluxes.

Also evident are the differences in latent heat fluxes for the different vegetation covers. The vegetation cover with a high concentration of trees (semi-deciduous) has high latent heat fluxes, because the deep roots of the trees can extract more soil moisture than the less endowed species of grass and shrubs.

These observations are reasonable considering the climatic conditions under which the data was collected. The data was collected in the dry season of the study area, which was characterized by harmattan winds (dry winds from the Sahara desert), and this corresponds to decreases in moisture in soils and plants. The plants exhibit distinct yellowing and rapid drying off and deciduousness (total leaf fall of trees and shrubs). Hutley et al. (2000) argue that during the dry season in the savanna, surface (0 – 50 cm) soil water content is typically very low (< 5 %) with little soil evaporation or transpiration from the understorey vegetation and by late dry season, tree transpiration accounts for about 80 – 90 % of evapotranspiration.



Figures 5.12A- 5.12E: Comparison of diurnal simulations of latent energy fluxes between burnt and unburnt savanna of northern Ghana (February 2003)

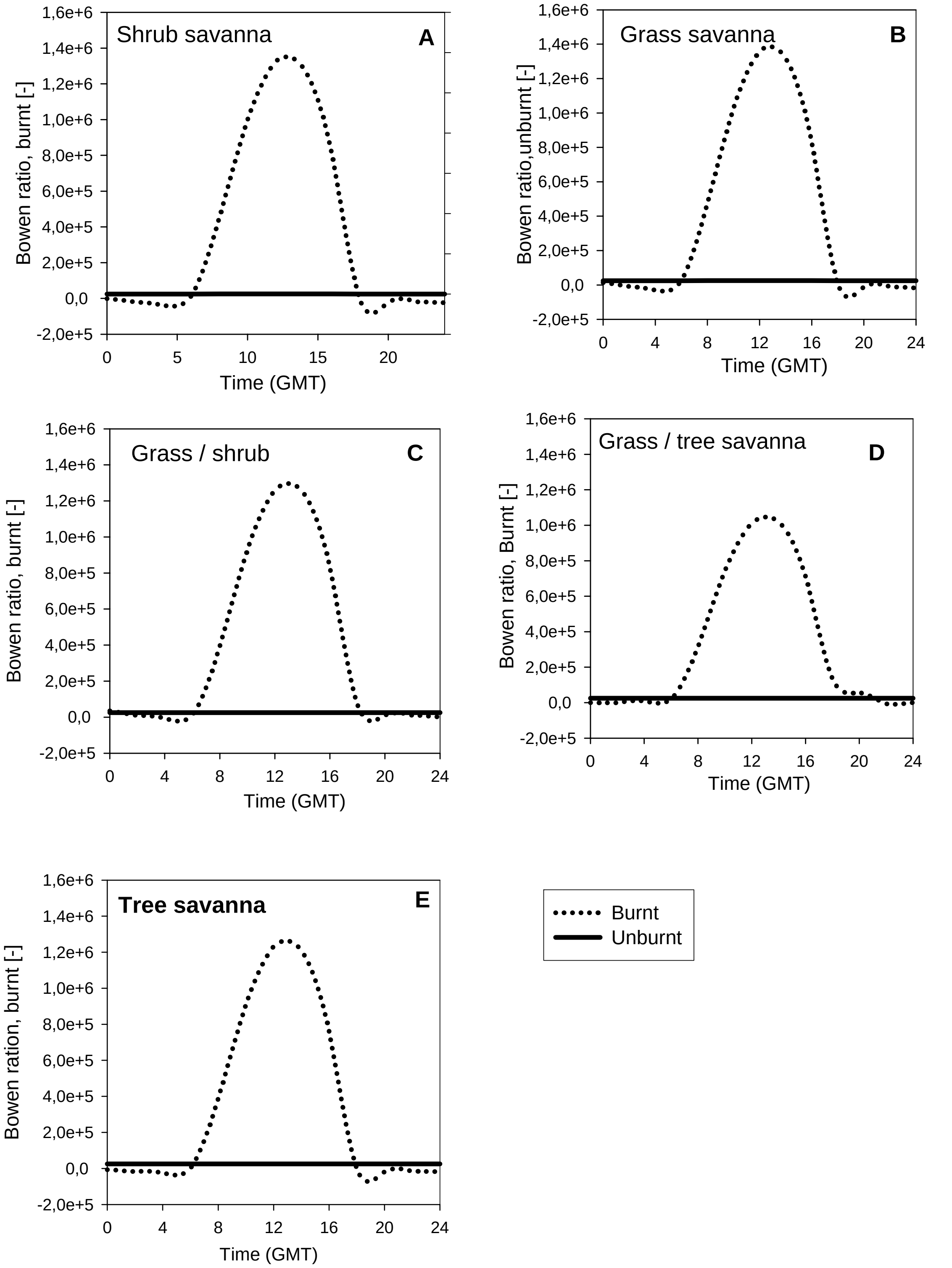
Once the leaves of the trees fall, transpiration ceases. The dry vegetation is eventually burnt, leaving only ash and charred material on the surface of the soil. These conditions drastically reduce the evapotranspiration (latent energy) to the barest minimum, and this can be safely assumed to be zero, thus the majority of the energy is dissipated as sensible energy heat fluxes.

5.8.2 Diurnal simulations of moisture indicators of burnt and unburnt plots

The prevailing conditions during the harmattan season imply marginal energy changes resulting from the arid climatic conditions. Additionally, the low values of albedo associated with the burnt savanna imply increased heating and sensible heat fluxes as illustrated in the discussion on the surface energy fluxes in the previous chapter. In particular, the partitioning of the available energy shifts drastically towards marginal values as a result of threshold changes in the surface energy fluxes induced by the bushfire. This energy partitioning is expressed by the moisture indicators, Bowen ratio and evaporative fraction. A detailed analysis of the simulation results for the moisture indicators is given in the ensuing analysis. Additionally, simulations of diurnal surface temperature are given, with comparison of maximum diurnal temperatures for both simulated and measured values.

Bowen ratio

Figures 5.13A-5.13E show the corresponding diurnal course in Bowen ratio for the respective experimental sites. The Bowen ratio ranges from 9.94 – 12.68 across the different vegetation cover types for the unburnt plots, but is relatively high for the burnt plots. Comparisons between the unburnt and burnt plots show infinitely high percentage changes in the Bowen ratio. Sharp differences can be observed between the burnt and unburnt savanna. In particular, the increased latent heat fluxes associated with the unburnt savanna result in a lower Bowen ratio as compared with the burnt case which shows an infinitely high Bowen ratio due to the almost zero latent heat fluxes. Additionally, the shapes of the Bowen ratio graphs for the burnt case are symmetrical or bell-shaped as compared to the unburnt case, which has irregular shapes. The diurnal trend of the Bowen ratio shows an increase for the burnt savanna until 1200 GMT when it reaches its maximum and then starts to decline, whereas that of the unburnt is zero (0). This can be explained by the fact that in the dry season, the area is characterized by leaf fall from the shrubs and trees. Further more, heat from the understorey during bushfires causes substantial leaf scorch and subsequent leaf fall. This is likely to reduce transpiration and fundamentally change the fraction of the available energy partitioned into sensible and latent energy heat fluxes. The very large Bowen ratio of the burnt condition is largely due to the fact that most of the energy is dissipated as sensible energy, and a relatively small portion is dissipated as latent energy, thus drastically increasing the ratio between the two forms of energy.

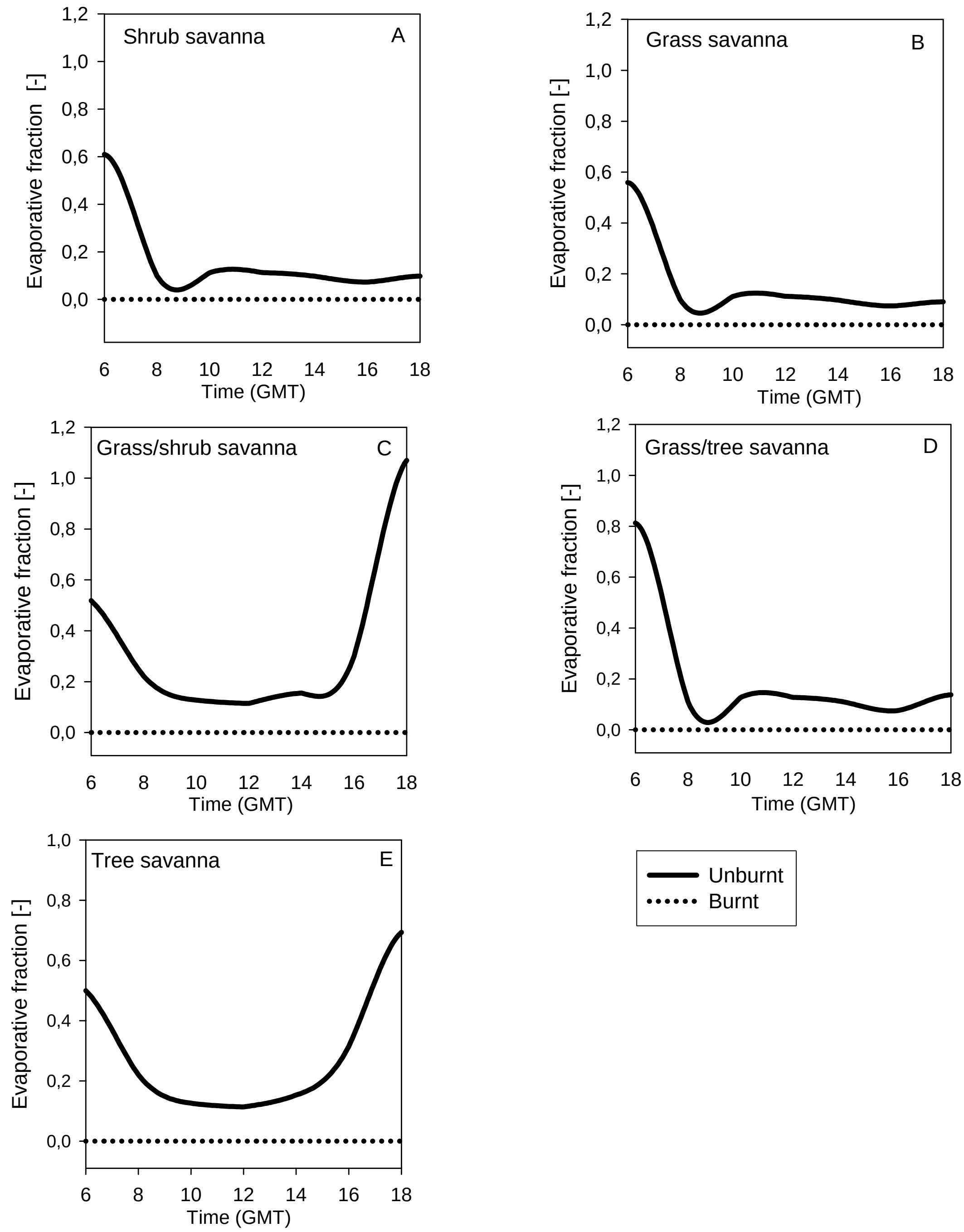


Figures 5.13A- 5.13E: Comparison of diurnal simulations of Bowen ratio between burnt and unburnt savanna of northern Ghana (February 2003)

Evaporative fraction

The graphs for the evaporative fraction for the respective sites are shown in Figures 5.14A- 5.14E. As in the case of the Bowen ratio, marked differences exist between the burnt and unburnt cases. Additionally, differences exist between plots (A, B, D) and (C, E). This may be due to the relative magnitudes of sensible and latent heat fluxes for the various vegetation cover types, in particular after 1400 GMT. More importantly, the unique shapes of the graphs are due to the sensitivity of the latent heat fluxes to the arid conditions. Particular care was taken to ensure that realistic values of the evaporative fraction are obtained by restricting the simulation times between 0600 and 1800 GMT.

The evaporative fraction of the unburnt plots ranged between 0.56 and 1.07, but that for the burnt was relatively small (7.85E -07 to 7.18E-04). The diurnal trend across the vegetation cover types was similar, declining from 0600 GMT and almost flattening between 1000-1400 GMT and increasing again (Figures 5.14A- 5.14E). Similar reasons advanced for the impact of bushfire on the Bowen ratio are applied here. The relatively high sensible heat and low latent heat immediately after dry season bushfires drastically reduces the evaporative fraction. The Bowen ratio and evaporative fraction are moisture indicators, and their values are mainly governed by the moisture condition of the area; however the evaporative fraction is a good measure, since it is bounded between 0 and 1, whereas Bowen ratio is not bounded.

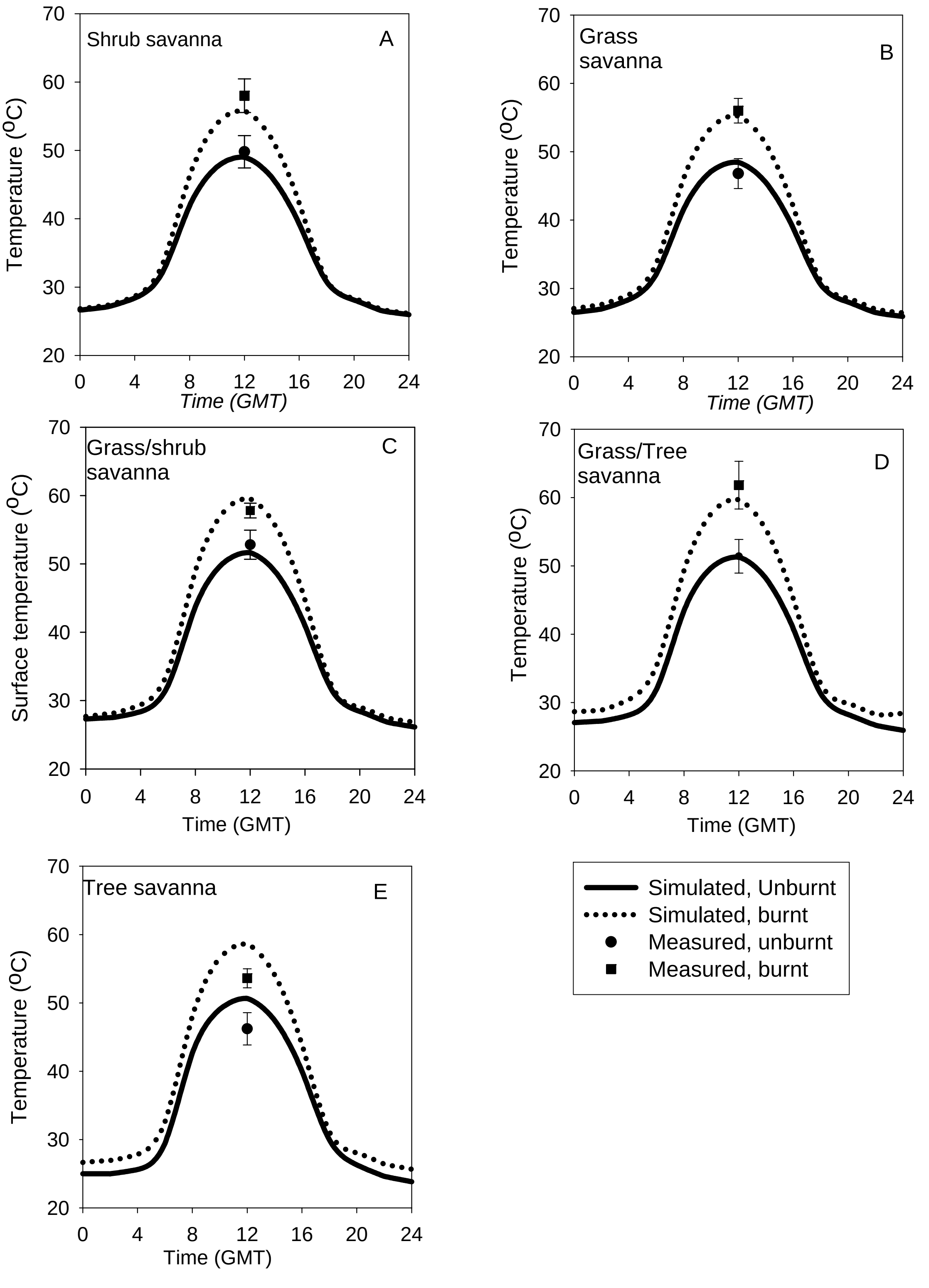


Figures 5.14A- 5.14E: Comparison of diurnal simulations of evaporative fraction between burnt and unburnt savanna of northern Ghana (February 2003)

Surface temperature

Figures 5.15A-5.15E show the diurnal temperature graphs for the respective experimental sites. To validate the accuracy of the BATS model in predicting surface temperature, measurements (with error bars) for diurnal maximum temperatures are shown on the respective plots for the experimental sites. Comparisons between the modelled and measured maximum diurnal temperatures show very good agreement for the sites shrub savanna, grass savanna, grass/shrub savanna and grass/tree savanna. However, those for the tree savanna show marked discrepancies. A close look at the measured data suggests the possibility of large measurement errors. In particular, it was observed that the temperature variability between measurements taken at five locations within the tree savanna experimental site was quite high (range of 8^{o}C). Additionally, comparison with sites of similar land cover and climatic conditions (e.g. tree/grass savanna) show marked differences.

Although they cannot be generalized, the results for the whole simulated diurnal temperature range, it can be inferred from the analysis that the BATS scheme simulates very well the maximum diurnal temperature under harmattan conditions.



Figures 5.15A- 5.15E: Comparison of diurnal simulations of surface temperature between burnt and unburnt savanna of northern Ghana (February 2003)

Conclusions

Bushfire is a frequent and extensive feature of the savanna of northern Ghana during the dry season and has been fundamental in shaping the interactions between climate, fire and vegetation. In this savanna, bushfire consumes the entire grass-dominated understorey, which results in a drastic reduction of albedo. This translates into an increase in net solar absorbed radiation, high sensible heat fluxes and very small latent heat fluxes. Additionally a high Bowen ratio and very small evaporative fraction were observed.

The net absorbed energy was similar across the vegetation cover types for the burnt (758 Wm^{-2}) and different for the unburnt plots (705-711 Wm^{-2}). The sensible heat ranged between 474 and 522 Wm^{-2} for the burnt and (408 and 455 Wm^{-2}) for the unburnt; latent heat was $\sim 10^{-4}$ for the burnt and between 57 and 64 Wm^{-2} for the unburnt plots.

5.9 Emissions from bushfire

It is now well recognised that the annual extent of biomass burning from the savanna fires is the predominant source of global biomass burning and associated greenhouse gas emissions (Hao and Liu, 1994; Andreae, 1997).

African savanna fires, almost all resulting from human activities, may produce as much of a third of the total global emissions from biomass burning (Hao et al., 1990; Cahoon et al., 1992; Stott, 1994). In addition, the savannas are likely to be affected by global environmental changes caused by global warming (Stott, 1991).

Bushfire is a source of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO_2). In addition, it is also a source of chemically active gases including carbon monoxide (CO), non-methane hydrocarbons, and nitric oxide. These gases, along with methane, lead to the chemical production of tropospheric ozone (another greenhouse gas).

The bushfires in the savanna of northern Ghana and their associated emissions from the system, are always a net source of carbon to the atmosphere in the dry season. In this section emission factors from similar environments were used to estimate the quantity of the emissions in the study area after a single fire.

5.9.1 Estimate of greenhouse gas emissions from bushfires

The emission factor from Hurst et al. (1994), estimated in a similar savanna environment, is applied for the computation. The estimated emissions are presented in Table 5.26. The highest gas emitted during the annual bushfires was CO_2, with mean values of 1053 – 2949 kg ha^{-1}; the lowest was N_2O, and this ranging from 0.11 to 0.19 kg ha^{-1}. Generally, the highest emissions were in the grass savanna and grass/tree savanna and the lowest from the shrub savanna. There were no consistent patterns between December and February emissions. However, in grass savanna and grass/tree savanna, there was an increase in emissions in February, except for N_2O in the grass/tree savanna. The other vegetation cover types showed a decrease in emissions from December to February.

These results are at variance with those of Saanark (1999), who estimated rather lower values in the study area around Dalun. This was a result of differences in fuel load values, which were lower than those measured in this study

Table 5.26: Estimated emissions from bushfires in northern Ghana (December 2002 and February 2003). Values are means and standard errors in parenthesis

Emission/Site	Shrub savanna		Grass savanna		Grass/shrub savanna		Grass/tree savanna		Tree savanna	
	Dec-2002	Feb - 2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003	Dec-2002	Feb-2003
C (Kg ha^{-1})	2160	1420	2640	3390	2640	1210	2770	3000	2430	1760
CO_2 (Kg ha^{-1})	1879 (65)	1235 (43)	2297 (79)	2949 (102)	2297 (79)	1053 (36)	2410 (83)	2610 (90)	2114 (73)	1531 (53)
CO (Kg ha^{-1})	168 (50)	111 (33)	206 (61)	264 (78)	206 (61)	94 (28)	217 (64)	234 (69)	189 (56)	137 (40)
CH_4 (Kg ha^{-1})	7.6 (0.26)	5.0 (0.17)	9.0 (0.32)	11.9 (0.41)	9.0 (0.31)	4.0 (0.15)	9.7 (0.33)	10.5 (0.36)	8.5 (0.29)	6.2 (0.21)
N (Kg ha^{-1})	22.0	14.6	23.0	24.0	24.0	13.0	25.0	22.0	20.0	15.0
NO_x (Kg ha^{-1})	4.6 (1.76)	3.1 (1.17)	4.8 (1.84)	5.0 (1.92)	5.0 (1.92)	2.73 (1.04)	5.25 (2.0)	4.62 (1.76)	4.2 (1.6)	3.15 (1.2)
N_2O (Kg ha^{-1})	0.17 (0.45)	0.11 (0.31)	0.18 (0.05)	0.18 (0.05)	0.18 (0.05)	0.10 (0.03)	0.19 (0.05)	0.17 (0.05)	0.15 (0.04)	0.16 (0.03)

Emission factors from Hurst et al. (1994) were used in the calculations except where noted. Emission factors represent the fraction of burned fuel
C and N emitted as each species.
Emission factors are as follows:
$CO_2 = 0.87 \pm 0.03$
$CO = 0.078 \pm 0.023$
$CH_4 = 0.0035 \pm 0.0012$
$NO_x = 0.21 \pm 0.08$
$N_2O = 0.0077 \pm 0.0021$, from Lobert, et al., 1994

5.9.2 Emissions at landscape level

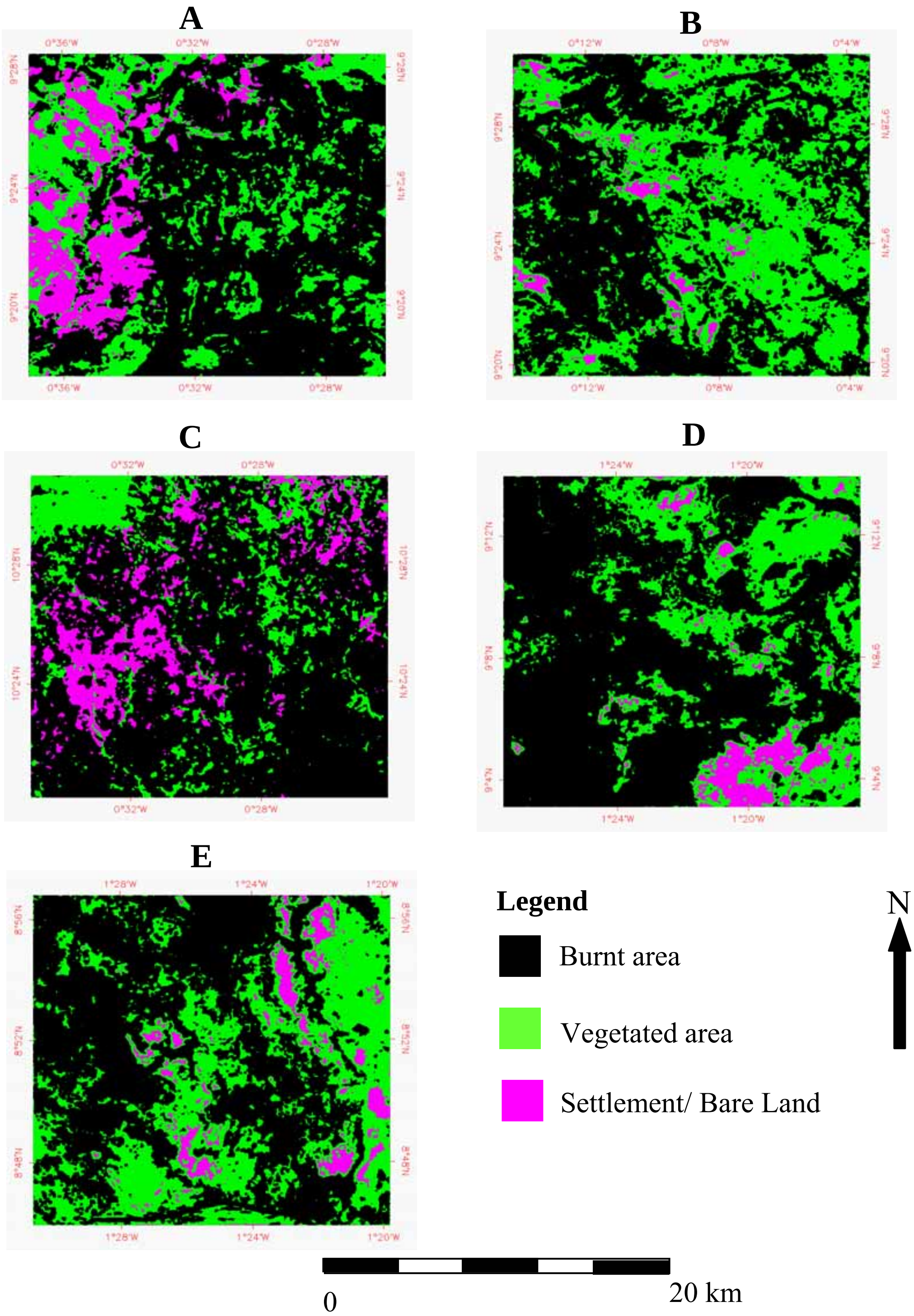
A large number of burnt scars were detected in the resized image classified in the dry season across the different vegetation cover types (Figures 5.23A-5.23E). The total classified area for each cover type was 40160 ha (about 20 km x 20 km). Over 50% of the area in the shrub savanna, grass/shrub savanna and grass/tree savanna was burnt, for the grass savanna and tree savanna these values were 30 % and 37 %, respectively (Table 5.27). Less than 50 % of these cover types in these areas were vegetated at the time of the satellite passage of the satellite except the grass savanna site, which was 54 %.

The above observation is consistent with the situation in the study area. Generally, large tracks of land are burnt during the dry season, and since the image used in this study was acquired in the dry season it was expected that most of the area should have been burnt, as this is the normal practice in the study area. However, it is important to mention that these burnt areas do not represent the entire dry season and are those burnt scars, captured by the satellite at the time of over pass and include recently burnt scars and active fire. It is possible that flushing of tree crowns and re-sprouting of vegetation can lead to the fading of fire scars. It can therefore be safely assumed that these estimates are closer to the values of late dry season bushfires than those of early dry season bushfires in the savanna of northern Ghana. Estimates of Table 5.27 pertaining to the late dry season are used to calculate the emissions from each vegetation cover type in the study area.

Table 5.27: Area and the percentage coverage of land cover types as classified from a Landsat 7 ETM, 14/ 03 / 2000

Land cover type/ Site	Shrub savanna	Grass savanna	Grass/shrub savanna	Grass/tree savanna	Tree savanna
			Burnt		
No. of pixels	267700	134827	305204	229033	164671
Area (ha)	24093	12134	27468	20613	14820
[a]% coverage	60	30	68	51	37
			Vegetation		
No. of pixels	115463	242396	79222	146485	207656
Area (ha)	10391	21816	7130	13184	18689
% coverage	26	54	18	33	46
			Settlement / Bare Land		
No. of pixels	63061	69001	61798	70706	73897
Area (ha)	5675	6210	5561	6364	6651
% coverage	14	16	14	16	17

[a] Percentage coverage calculated from a total area of 40160 ha and total of 446224 pixels (resized Landsat image used for the image classification).



Figures 5.16A-5.16E: Maps of burnt scars in five sites (resized 20 km x 20 km) (A=Shrub savanna, B = Grass savanna C = Grass / shrub, D = Grass/tree savanna and E = Tree savanna) in the savanna of northern Ghana. Maximum likelihood algorithm was used to classify the burnt scars using Landsat 7 ETM, 14 / 03 / 2000

Based on Tables 5.26 and 5.27, the emissions from the burnt vegetation cover types were estimated (see Table 5.28). Generally, grass/tree savanna and grass savanna released the highest amount of emissions and the tree savanna the lowest. The highest amount of gas that was emitted was CO_2, ranging from 3 x 10^4 to 5 x10^4 tons; the lowest was N_2O between 2.2 and 5.2 tons. The cumulative total for all vegetation cover types was 1.7 x 10^5 tons. Menaut et al. (1991) estimated that 438 x 10^6 tons of CO_2, 27 x 10^6 tons of CO, 1.75 x 10^6 tons of CH_4, 130 x 10^6 tons of NO and 7.6 x 10^6 tons were released in West Africa. If the emissions of this study are extrapolated to the whole of the savanna of northern Ghana, this area is likely to contribute significantly to the total emissions of West Africa, which will have climatic implications. Furthermore, the calculated emissions are locally significant, especially considering the fact that the releases are seasonal phenomena concentrated in the dry season.

Table 5.28: Estimated annual emissions from burning different vegetation cover types in the savanna of northern Ghana

Emission/site	Shrub savanna	Grass savanna	Grass/shrub savanna	Grass/tree savanna	Tree savanna	Total
			t yr^{-1}			
CO_2	29756	35783	28924	53800	22689	170950
CO	2674	3203	2582	4823	2030	15311
CH_4	120	144	110	216	92	682
NO_x	75	61	75	95	47	353
N_2O	2.6	2.2	5.2	3.5	2.4	16.3

5.9.3 Implications of the emissions

The calculated emissions may be locally significant, especially when the releases are annual, and concentrated during the dry season. CO_2, CH_4 and N_2O are greenhouse gases that directly contribute to the heat retention within the atmosphere. CH_4 and N_2O have, respectively, 21 and 290 times the global warming potential of CO_2. Chemically active gases like CO_2, CH_4 and NO lead to photochemical production of ozone (O_3) in the troposphere, and higher levels could be lethal to plants and animals (Levine, 1991). Particulate matter emissions will continue to have significant policy implications, given their potential to reduce visibility, and cause health problems including increased respiratory symptoms and increased mortality (Beer and Meyer 2000; Johnston et al., 2002).

Conclusions

This study quantifies locally significant amounts of gaseous and particulate emissions to the atmosphere through biomass burning during bushfires in the savanna of northern Ghana. The results show the contribution of the bushfires to the regional CO_2 emissions to the about 1.7×10^5 tons. It should be noted that there are possible sources of error in these calculations resulting from inaccurately determined burnt areas as a result of fading of burnt scars and a limited temporal data set. However, figures calculated using contemporaneous spatial data sets such as those in this study indicate fairly accurately the contribution of emissions from the study area. These figures help to quantify the perturbation of the atmosphere associated with emissions from the study area and will assist in quantifying the effect emissions have on ecosystems within the study area and beyond. Fire mosaic detection techniques may be used to assist in the regional monitoring of fire activity. Mapping of fire activity by satellite provides a fast, reliable and inexpensive method of regional monitoring. The production of fire maps is important for the land managers to achieve an appropriate burning frequency. In addition, coupling vegetation data with fire mosaic maps allows a comparison of vegetation types burnt and may give insight for fire ecologists into the susceptibility and resilience of vegetation communities.

6 SUMMARY AND CONCLUSIONS

6.1 Summary

The soils of the study area are predominantly Lexisols, Leptosols, Plinthsols, Acrisols and Luvisols. Furthermore, extensive areas are covered by groundwater groundwater lateritic soils that have developed over both the Voltaian shales and granites. The characteristic vegetation cover of the zone is woodland savanna, which consists of open stands of trees, the crowns of which form a canopy.

Additionally, the dominant sand and silt fractions of the soil are as a result of deposits from the harmattan winds. Low values of CEC, SOM and intermediate quantities of exchangeable cations (K, Ca, Mg and Na) were observed in the soils. The soils are moderately acidic with very low organic carbon (< 1 %) and total nitrogen (< 0.1 %) and also P deficient.

6.1.1 Vegetation heterogeneity

At the landscape level, five land cover types were identified using remote sensing:

- Savanna woodland
- Open savanna woodland
- Mixture of grass/herbs fallow and crop field
- Settlement
- Water body

At the site level, four vegetation groups were identified:

- Widely open savanna woodland
- Grass/herb fallow with scattered trees (75-150 trees ha^{-1})
- Open savanna woodland (75-150 trees ha^{-1})
- Closed savanna woodland (>150 trees ha^{-1})

Furthermore, descriptive diagrams were used to describe the different vegetation formations in the study area. The diagrams portray the heterogeneity of the vegetation.

Observations in the field indicate that there are actually no pure stands in the study area but rather a mixture of grasses, shrubs and trees. There are isolated areas of grass cover, which are mostly fallowed or degraded areas, and woodlands with varying tree density. Typically, many of the trees are scattered without a close canopy in many places, enabling sufficient light to reach the ground for the growth of grass and shrubs as long as there is sufficient soil moisture.

6.1.2 Fuel load and nutrient losses

The highest fuel load measured was 7.8 t ha^{-1} in the grass savanna with the herbaceous component (mainly grass) being the dominant fuel. Vegetation cover type and season of sampling affected the total fuel load. Grass and grass/tree savannas recorded substantial losses of fuel load and carbon, but losses between the seasons did not show any consistent trend.

High nutrient stocks and losses were measured across all the different vegetation cover types, with grass and grass/tree savanna sites recording the highest; shrub and tree savanna sites recorded the lowest. Sites with high herbaceous plant material will have a higher fuel load and subsequently experience higher nutrient losses as a result of the annual bushfires. The net losses of N, P and K under annual bushfires in the savannas of northern Ghana were estimated to be approximately 10 – 22 kg ha^{-1}, 1-7 kg ha^{-1} and 2-12 kg ha^{-1}, respectively.

6.1.3 Bushfire impact on soil properties, albedo and soil temperature

Soils sampled before and after burning suggest changes in soil chemistry in a manner that increases the tendencies of soils to have high N, K, Na, , pH and % sand , but low OC, SOM, P, Ca, Mg, CEC, % clay and silt. While short-term benefits of fires on soils such as increased levels of pH and some available nutrients are ideal, there are concerns about long-term loss in nutrients and impaired productivity (Tiedemann et al., 2000). Results suggest that the severity of bushfires should be closely monitored to prevent irreversible breakdown of soil minerals, because of the influence on chemical and physical processes.

Bushfires in this savanna are frequent and persistent and have been fundamental in shaping the dynamics between fire and vegetation. The grass-dominated understorey is consumed annually and this is likely to impact on the surface albedo. Surface albedo decreased from 0.22 on the unburnt plots to 0.06 on the burnt plots. Pre-fire albedo was different for the different vegetation covers, but post fire was similar. Furthermore the soil surface temperature increased from 46^{o}C on the unburnt to 62^{o}C on the burnt plots. Furthermore, simulation results show that net absorbed radiation, sensible heat and Bowen ratio increased from unburnt to burnt, but latent heat and evaporative fraction were lower.

6.1.4 Carbon and nitrogen emissions

Biomass burning from the savanna fires is the predominant source of global biomass burning and associated greenhouse gas emissions. The highest gas emitted during the fire was CO_2 with a mean value of 1053 – 2949 kg ha^{-1} and the lowest N_2O, ranging from 0.11 to 0.19 kg ha^{-1}. Generally the highest emissions were from the grass savanna and grass/tree savanna and the lowest from the shrub savanna.

Classification of burnt areas were carried out using cloud free Landsat 7 ETM + image (14 /03 / 2000). The total classified area for each vegetation type was 40160 ha. Over 50% of the area in the shrub savanna, grass/shrub savanna and grass/tree savanna were burnt; for grass savanna and tree savanna this was 30% and 37%, respectively. Less than 50% of these cover types in these areas were vegetated at the time of satellite passing except the grass savanna site, where 54% of the area was covered with vegetation.

The main gas emitted from the mapped burnt areas was CO_2 ranging from 3×10^4 to 5×10^4 tons and the smallest amount of gas released was N_2O ranging from 2.2 to 5.2 tons; the cumulative total of CO_2 released from all the sites was 1.7×10^5 tons. These emissions are important in the study area and contribute to the greenhouse effect and global warming debate.

6.2 Conclusions

In the nutrient poor-savannas of northern Ghana, long-term effects of repeated bushfires on the ecosystem lead to serious net losses of N. Furthermore, the present study suggests that biological fixation and wet depositions may be of insufficient magnitude to replace the lost N. To reduce the likelihood of progressive land degradation, the use of fire in land preparation needs to be reduced. This could be achieved by decreasing the frequency of fires either temporally or spatially, through promoting patchy fires such as can occur early in the dry season. Prevention of bushfires through mass education should be encouraged. Prophylactic measures such as educating people about the outbreaks and consequences of fires on the environment as a whole would be a step in the right direction.

Seasonal and fire-induced shifts in albedo affect the amount of net solar radiation (net short wave radiation) retained at the surface of the soil. The high soil surface temperature observed in post-fire soil surface temperature is probably due to the high net absorbed solar radiation as a result of lower albedo, increasing the sensible heat flux, since evapotranspiration is lower. Increased sensible energy used in surface heating could have significant impacts on local to regional atmospheric circulations and climate. At the local scale, depending on the aerodynamic changes in savanna vegetation following fire, enhanced sensible fluxes over patches of burnt landscape (in order of 100 km^2) could produce localised areas of convergence and divergence and associated mesoscale circulation systems. Such circulation patterns may lead to an increase in spatially fixed convective cloud development and precipitations following fire until fluxes have returned to pre-bushfire conditions. It has been shown that landscape contrasts in albedo on burnt areas and their surroundings can produce quite strong mesoscale circulation systems. Such circulations are known to be capable of producing intense, spatially fixed cloud convection and precipitation under suitable environmental conditions (Keenan et al. 2000; Beringer et al., 2001b).

This study quantifies locally significant amounts of gaseous and particulate emissions to the atmosphere through biomass burning in the savanna of northern Ghana. The results show a possible contribution of the bushfires to the regional CO_2 emissions to the about 1.75 x 10^6 tons. It should be noted that there are possible sources of error in these calculations resulting from inaccurate burnt areas as a result of fading of burnt scars and a limited temporal data set. However, figures calculated using contemporaneous spatial data sets as the ones in this study give much accurate indication of the contribution of emissions from the study area. These figures help quantify the perturbation of the atmosphere associated with emissions from the study area and will assist in quantifying the effect emissions have on ecosystems within the study area and beyond. Fire mosaic detection techniques may be used to assist in the regional monitoring of fire activity. Mapping of fire activity by satellite provides a fast, reliable and inexpensive method of regional monitoring. The production of fire maps is important for the land managers to achieve an appropriate burning frequency. In addition, coupling vegetation data with fire mosaic maps allows a comparison of vegetation types burnt and may give insight for fire ecologists into susceptibility and resilience of vegetation communities.

In conclusion the following points are highlighted:

- The nutrient status of the study region is very low and the soil structure poor.
- Though the vegetation of the area has been characterized before, this is the first time a structural description is done using profile diagrams and codes.
- The fuel load is mainly influenced by the structure of the vegetation cover type.
- The carbon and nutrient stocks are largely influenced by the quantity of the fuel load.
- High amounts of nutrients were transferred to the atmosphere. Net losses were measured for N, P and K, with N being the highest.
- Albedo was drastically reduced after bushfire, thereby altering surface energy budget and moisture indicators. In particular, more observational data on energy fluxes and moisture indicators are needed to validate simulated values.
- The study quantifies locally significant amounts of gaseous emissions using the remote sensing technique.

6.3 Outlook

The outlook for the future includes the following:

- Patch mosaic burning (an emerging paradigm) should be encouraged to reduce the destructive nature of the late bushfires. Additionally, intensive and extensive educational campaigns against bushfires, especially focusing on their impact on nutrient stocks, are necessary.
- Research on the role of biological N_2 fixation is necessary to adequately explain the sustainability of the savanna ecosystem despite large losses of N during annual bushfires.
- Detailed study is needed to assess how bushfires induce changes in surface energy and moisture indicators, using measured data to validate the simulated results.

7 REFERENCES

Abatania L and Albert H (1993) Potentials and constraints of legume production in the farming systems of Northern Ghana. In: Proceedings of the Third Workshop on Improving Farming Systems in the Interior Savannah Zone of Ghana, Nyankpala Agricultural Experimental Station, NAES, Tamale, Ghana 170-181.

Abekoe MA and Tiessen H (1998) Fertilizer P transformations and P availability in hillslope soils of northern Ghana. Nutrient Cycling in Agroecosystem 52, 200-204.

Abekoe MA and Tiessen H (1998) Fertilizer P transformations and P availability in hillslope soils of northern Ghana. Nutrient Cycling in Agroecosystem 52, 200-204.

Agyapong GT, Duadze SEK, Annor J, Donyuo SSB, Tetteh E and Gyeabour A (1999) Land use and land cover map of Ghana. Technical Bulletin No. 3. Remote Sensing Applications Unit, University of Ghana, Legon, Accra.

Ahlgren IF and Ahlgren CE (1960) Ecological effects of forest fires. Bot. Rev. 26, 483–533.

Anderson AN, Braithwaite RW, Cook GD (1998) Fire Research for Conservation Management in Tropical Savannas: Introducing the Kapalga Fire

Andrea MO (1997) Emissions of trace gases and aerosols from the southern Africa savann fires. In: van Wilgen BW, Andreae MO, Goldammer JG and Lindesay JA (eds), Fire in the southern African savannas: ecological and atmospheric perspectives. Witwatersrand University Press, Johannesburg, 161-184.

Arocena JM and Opio C (2003) Prescribed fire-induced changes in properties of sub-boreal forest soils. Geoderma 113, 1-16.

Avissar R and Pielke R (1989) A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology. Mon. Wea. Rev., 117, 2113-2136.

Baker HG (1962) The Ecological study of vegetation of Ghana. In: Willis, J.B. 1962. Agricultural and land use in Ghana. Ghana Ministry of Food and Agriculture, Oxford University Press, London. pp. 451.

Balandreau J (1976) Fixation rhizosphérique de I'azote (C_2H_2) en savanna de Lamto. Rev. Ecol. Biol. du Sol. 13, 529-544.

Bastiaanssen WG (1995) Regionalization of surface flux densities and moisture indicators in composite terrain. PhD thesis, Wageningen Agricultural University.

Beer T (1991) The interaction of wind and fire. Boundary-Layer Meteorology 54, 287-308.

Beer T and Meyer CP (2000) The impact on the environment-The atmosphere. In Fire! The Australian experience: Proceedings from the National Academies Forum Seminar. National Academies Forum, Canberra, ACT, Australia, 59-77.

Belward AS, Kennedy PJ and Grégoire JM (1994) The Limitations and Potential of AVHRR GAC data for Continental Scale Fire Studies, International Journal of Remote Sensing, 15, 2215-2234.

Benneh G and Dickson KB (1988) A new geography of Ghana. Longman Group Ltd, Essex, England.

Benzie JAH (1986) The distribution, abundance, and the effects of fire on mound building termites (Trinervitermes and Cubitermes spp., Isoptera: Termitidae) in northern guinea savanna. West Africa. Oecologia (Berl.), 70, 559-567.

Beringer J, Tapper NJ, McHugh I, Chpin FS, III, Lynch AH, Serreze MC and Slater Ag (2001b) Impact of Artic circle treeling on synoptic climate. Geophysical Research Letters 28, 4247-4250.

Beringer J, Hurtley LB, Tapper NJ, Coutts A, Kerley A, and Grady PO (2003) Fire impacts on surface heat, moisture and carbon fluxes from a topical savanna in northern Australia. International Journal of Wildland Fire, 12, 333-340.

Bijker HJ, Sumner PD, Meiklejohn KL and Bredenkamp GJ (2001) Documenting the effects of veld burning on soil and vegetation characteristics in giant’s castle game reserve, Kwazulu-Natal, Drakensberg. South Africa Geographical Journal 83, 28-33.

Birch HF (1958) The effect of soil drying on humus decomposition and nitrogen availability. Plant and Soil 10, 9-31.

Bird MI and Cali JA (1998) A million - year record of fire in sub-Saharan Africa. Nature Vol. 394, 767-769.

Bird MI, Veenedaal EM, Moyo C, Llyod J, Frost P (2000) The effect of fire and soil texture on soil carbon in a sub-humid savanna (Matopos Zimbabwe). Geoderma 94, 1-90.

Boo RM, Peláez DV, Bunting SC, Elía OR, and Mayor MD (1996) Effect of fire on grasses in central semi-arid Argentina. Journal of Arid Environments 32, 259-269.

Bottomley RD (1999) Mapping Rural Land Use and Land Cover Change In Carroll County, Arkansas Utilizing Multi-Temporal Images Campbell JB, 1987, Introduction to remote sensing (New York: Guilford Press), 500-501.

Bourgeau-Chavez LL, Harrrel PA, Kasischke ES and French, NHF (1997) The Detection and Mapping of Alaska Wildfires Using a Spaceborne Imaging Radar System. International Journal of remote Sensing, 18, 355-375.

Bourliére F and Hadley M (1983) Present-day savannas: An overview. In: Bourliére, F (ed), Ecosystems of the world, vol. 13, Tropical Savannas Elsevier, Amsterdam, 1-17.

Bouyoucos GH (1962) Hydrometer method improved for making particle size analysis of soils. Agronomy Journal 54, 454-465.

Bowen IS (1926) The ratio of heat losses by conduction and by evaporation from any water surface. Physical Review 27, 779-787

Bowman DMJS and Wilson BA (1988) Fuel characteristics of coastal monsoon forests, Northern Territory, Australia. Journal of Biogeography 15, 149-158.

Bowman DMJS, Zhang Y, Walsh A, Williams RJ (2003) Experimental comparison of four remote sensing techniques to map tropical savanna fire-scar using Landsat-TM imagery. International Journal of Wildland Fire 12, 341-348

Boyer DE and Dell JD (1980) Fire effects on Pacific North-west For. Range Exp. Stn. Portland.

Bray RH and Kurtz LT (1945) Determination of total, organic and available forms of phosphorous in soils. Soil Science 59, 39-45.

Bremer JD and Ham JM (1999) Effect of spring burning on the surface energy balance in a tall grass prairie. Agricultural and Forest Management 97, 43-54.

Bresci E (1992) Land use classification from remotely sensed data. Unpublished Report of Institute for Hydrology, Water Resources and Environmental Engineering, Ruhr University of Bochum, Bochum.

Brieb K, Ginati A, Sommer K (1996) A small satellite solution for the fire detection and monitoring from space. Acta Astronautica 39, 447-457.

Brookman-Amissah J, Hall JB, Swaine MD and Attakorah JY (1980) A Re-assessment of a fire protection experiment in North-Eastern Ghana Savanna. Journal of applied Ecology 17, 85-99.

Brustet J.M, Fontan VJ, Podiare A and Lavenu F (1991) Detection and Characterization of Active Fires in West Africa with LANDSAT Thematic Mapper and NOAA. 5th International Colloquium, Physical Measurements and Signatures in Remote Sensing. Courchevel. France. 14-18 January 1991.

Cahoon DR, Stocks BJ, Levine JS, Coffer III, WR, and O' Neil KP (1992) Seasonal distribution of African savanna fires. Nature; 359, 812-815.

Campbell JB and Browder, JO (1995) Field data collection for remote sensing analysis: SPOT data Rondonia, Brazil. International Journal of Remote Sensing, 16, 333-350.

Chandler CP, Cheney P, Thomas L, Trabaud and Williams D (1983) Fire forestry. Vol. 1: Forest Fire Behavior and Effects. Hon Wiley & Sons, New York.

Chen F and Duhia J (2001) Coupling an Advanced Land- Surface/Hydrology Model with the Penn State/NCAR MM5 Modelling System, part I: Model Implementation and Sessitivity. Mon. Weath. Rev., 129, 569-585.

Cheney NP (1981) Fire behaviour, chap.7 In: Gill AM, Groves RH, Noble IR (eds). Fire and the Australian biota. Aust Acad Sci, Canberra, 151- 175.

Cheney NP Gould JS and Catchpole WR (1993) The influence of fuel, weather and fire shape variables on fire- spread in grasslands. International Journal of Wildland Fire 3, 31-44.

Christiansen MN and Foy CD (1979) Fate and function of calcium in tissue. Commun. Soil Sci. Plant Anal. 10, 427-442.

Cole, MM (1986) The Savannas: biogeography and geobotany. Academic Press, London.

Contreras-Hermosilla A (2000) The underlying causes of forest decline. Occasional Paper No. 30. Centre for International Forestry Research (CIFOR), Sindang Barang, Bogor, Indonesia, 25.

Cook GD (1992) The effects of fire on nutrient losses from Top End Savannas. In: I. Moffatt and A. Webb (eds), Conservation and Development Issues in Northern Australia. North Australia Research Unit, Darwin, 123-9.

Cook GD (1994) The fate of nutrients during fires in a tropical savanna. Australian Journal of Ecology 19, 359-365.

Cook GD, So HB, Dalal RC (1992) Structural degradation of two vertisols under continuous cultivation. Soil and Tillage Research 24, 47-64.

Cosby BJ, Hornberger GM, Clapp RB and Ginn TR (1984) A statistical exploration of relationships of soil moisture characteristics to the physical properties of soils. Water Resour. Res., 20, 682-690.

Cotton FA and Wilkinson G. (1962) Advanced inorganic chemistry: a comprehensive text. Interscience Publishing Co. John Wiley & Sons, New York.

Cumming DHM (1982). The influence of large herbivores on savanna structure in Africa. In: Huntley BJ and Walker BH (eds), Ecology of tropical Savannas, Springer-Verlag, New York:, 217-245.
Curtin D, Campbell CA, Jalil A (1998) Effects of acidity on mineralization: pH-dependence of organic matter mineralization in weakly acidic soils. Soil Biology and Biochemistry 30, 57-64
Dale PER (1979) A pragmatic study of Dansereau's universal system for recording vegetation: application in South-East Queensland, Australia. Vegetatio 40, 129-133.
Dansereau P (1951) Description and recording of vegetation upon structural basis. Ecology 32, 172-229.
Dansereau P (1958) A universal system for recording vegetation. Contr. Bot. Univ. Montreal No. 72.
Dansereau P, Buell PF, Dagon R (1966) A universal system for recording vegetation. II. A methodological critique and an experiment. Sarracenia.
Dastoor A and Krishnamurti TN (1991) The landfall and structure of a tropical cyclone: The sensitivity of model predictions to soil moisture parameterizations, Boundary Layer Meterol. 55, 345-380.
Daubenmire R (1968) Ecology of fire in grasslands. Advances in Ecological Research 5, 209-266.
Dawidson E and Nilsson C (2000) Soil organic carbon in upper east region, Ghana: Measurements and Modelling. Department of Physical Geography, Lund University.
Deardoff JW (1978) Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. J. Geopys. Res., 83 (C4), 1889-1903
Debano LE, Neary DG, Ffolliot PF (1998) Fire´s effects on ecosystems. Wiley, New York.
Dickinson RE (1991) Global change and terrestrial hydrology: Areview, Tellus, 43AB, 176-181.
Dickinson RE and Kennedy PJ (1991) Land surface hydrology in a general circulation model: Global and regional fields needed for validation. Surv. in Geophys. 12, 115-126
Dickinson RE and Kennedy PJ (1992) Impacts on regional climate of Amazon deforestation. Geophys. Res. Letters, 19, 1947-1950.
Dickinson RE, Henderson-Sellers A and Kennedy PJ (1993) Biosphere-Atmosphere-Transphere Scheme (BATS) Version 1e as Coupled to the NCAR Community Climate Model. NCAR Technical Note. NCAR.
Dickinson RE, Henderson-Sellers A, Rosenzweig C and Sellers PJ (1991) Evapotranspiration models with canopy resistance for use in climate models, a review, Agricultural and Forest Meteorology Journal, 54, 375-388.
Duriscoe DM and Wells WG (1982) Effects of fire on certain physical properties of selected chaparral soils.. In: Conrad CE and Oechel WC (eds) Proc. Symp. Dynamics and management of Mediterranean-type ecosystems. U. S. For. Serv. Gen Tech. Rep. PSW-58. Pac. Southwest For. Range Exp. Stn. Berkeley, CA, 594.
Dyrness CT and CT Youngberg (1957) The effects of logging and slash burning on soil structure. Soil Sci. Soc. Am. Proc. 21, 444-447.

Dyrness CT, Van Cleve K, and Levison JD (1989) The effect of wildfire on soil chemistry in four forest types in interior Alaska. Can. J. For. Res. 19, 1389-98.

Dywer E, Pereira JMC, Gregoire JM, DaCamara CC (2000) Characterization of the spatio-temporal patterns of global fire activity using satellite imagery for the period April 1992 to March 1993. Journal of Biogeography 27, 57-69.

Eastwood JA, Plummer SE, Wyatt BK and Stocks BJ (1998) The Potential of SPOT Vegetation Data for Fire Scar Detection in Boreal Forests. International Journal of Remote Sensing.

Edwards A, Hauser P, Anderson M, McCartney J, Armstrong M, Thackway R, Allan G, Hempel C, Russell-Smith J (2001) A tale of two parks: contemporary fire regimes of Litchfield and Nitmiluk national Parks, monsoonal northern Australia. International Journal of Wildland Fire 10, 57-69.

Ekekpi GK., Aalangdong OI., Yakubu SM and Agyare WA (2000) – A review of natural resources management for agricultural production in the Northern Region.

Elvidge CD, Hobson VR, Baugh KE, Dietz JB, Shimabukuro YE, Krug T, Novo E, Echavarria FR (2001) DMSP-OLS estimation of tropical forest area impact by surface fires in Roraima, Brazil: 1995 versus 1998. International Journal of Remote sensing 22, 2661-2673.

Eva H and Lambin EF (1998) Remote Sensing of Biomass Burning in Tropical Regions: Sampling Issues and Multisensor Approach. Remote Sensing Environment, 64, 292-315.

Evans CC and Allen SE (1971) Nutrient losses in smoke produced during heather burning experiment. Oikos, 22, 149-154.

FAO Revised legend of the FAO-UNESCO Soil map of the world. World Soil Resources. Rep. 60, Rome 1988.

Fast JD and McCorcle MD (1991) The effect of heterogeneous soil moisture on a summer barroclinic circulation in the central United States, Mon. Weather Rev., 119, 2140-2167.

Feller MC (1982) The ecological effects of slush burning with particular reference to British Columbia: a literature review: Land Management Report No. 13. Province of British Columbia Ministry of Forests. Forest Practices Code of British Columbia Act (FPC), 1995. Forest Prevention and Suppression Rgulation. Ministry of Forests Victoria, BC.

Fournier A (1991) Phénologie, croissance et production végétales dans quelques savanes d' Africa de I' Ouuest. Variation selon un gradient climatique. Ph.D. thesis, Université Paris IV.

Frederiksen P, Langaas and Mbaye M (1990) NOAA-AVHRR and GIS-based Monitoring of Fire Activity in Senegal- a provitional Methodology and Potential Applications. In: Goldammer JG (ed.), Fire in the tropical Biota, Springer Verlag, Berlin-Heidelberg- New York, 400-417.

Frost PGH and Robertson F (1987). The ecological effects of fire in savannas. In: BH Walker (ed). Determinants of tropical savannas. IRL Press, Oxford, 93-140

Fugger WD (1999) Evaluation of Potential Indicators for Soil Quality in Savanna Soils in Northern Ghana (West Africa). Ph.D. Thesis, University of Göttingen.

Fuller DO (2000) Satellite remote sensing of biomass burning with optical and thermal sensors. Progress in Physical Geography 24, 543-561.

Fuller DO and Fulk M (2001) Burned area in Kalimantan, Indonesia mapped with NOAA-AVHRR and Landsat TM imagery. International Journal of Remote sensing 22, 691-687

Ghana Statistical Service (2002) Population and Housing Census of Ghana. Special Report on 20 Largest Localities. Ghana Statistical Service, Accra, Ghana

Gill AM, Ryan PG, Moore PHR, Gibson M (2000) Fire regimes of World Heritage Kakadu Park, Australia. Austral Ecology 25, 616-625

Gillon C (1983) The fire problem in tropical Savannas. In: Bourliere F (ed), Ecosystems of World, vol. 13: Tropical Savannas. Elsevier, Amsterdam, 617-641.

Giovanni G, Luchessi S, Giachetti M (1988) Effects of heating on some physical and chemical parameters related to soil aggregation and erodibility. Soil Sci. 146, 255-262.

Giovanni G, Luchessi S, Giachetti M (1990) Effects of heating on some physical and chemical parameters related to soi fertility and plant growth. Soil Science 149, 344-350.

Giri C and Shrestha S (2000) Forest fire mapping in Huay Kha Khaeng Wildlife Sanctuary, Thailand. International Journal of remote Sensing 21, 616-625

Goldammer JG (1990) Fire in the tropical biota: Ecosystems processes and global change. Springer-Verlag, Berlin.

Goldammer, JG (1993). Feuer in Waldökosystemtemen der Tropen and Subtropen. Basel. Birkhäuser, pp 251.

Gordon C and Amatekpor JK (1999) The Sustainable Integrated Development of the Volta Basin in Ghana. Volta Basin Research Project, Accra, Ghana pp 159.

Greenwood DJ (1968) Measurement of microbial metabolism in soil. In: Gray, TRG, Parkinson, D (Eds), The Ecology of Soil Bacteria. Liverpool Univ. Press, Liverpool.

Greenland DJ and Nye PH (1959) Increases in the carbon and nitrogen contents of tropical soils under natural fallows. Journal of Soil Science 9, 284-299.

Grier CE (1975) Wildfires effects on nutrient distribution and leaching in a coniferous ecosystem. Can J. For. Res. 5, 599-609.

Hao WM Liu M and Crutzen PJ (1990) Estimates of annual and regional releases of CO_2 and other trace gases to the atmosphere from fires in the tropics, based on the FAO statistics for the period 1975-1980. In: Goldammer JG (ed), Fire in the tropical biota: ecosystem processes and global challenges, Springer-Verlag, Berlin, 440-462.

Hao WM, Ward DC, Olbu GJ and Baker SP (1996) Emission of CO_2, CO, and Hydrocarbons from Fires in Diverse African Savanna Ecosystem. Journal of Geophysical Research, 101, 23577-23584.

Hao WM and Liu MH (1994) Spatial and temporal distribution of tropical biomass burning. Global Biogeochemical Cycles 8, 495-503.

Haydon DT, Friar JK, Pianka ER (2000) Fire-driven dynamic mosaics in the Great Victoria Desert, Australia. Fire geometry. Landscape Ecology 15, 373-381.

Hauffe H-K (1989) Site characterization of the West Ridge Upland Experiment Area (NAES). In: Nyankpala Agricultural Research Report, No.6, Annual Report 1987/88, NAES, 139-154.

Herland YR, Frelander K, Soini H, Kuoremaeki and Ruokari A (1997) Satelitte-based Forest Fire Detection for Fire Control in Boreal Forest. International Journal of Remote Sensing., 18, 2641-2656.

Hernández-V and López-H (2002) Pérdida de nutrimentos por la quema de la vegetation en una sabana de Trachypogon. Rev. Biol. Trop. 50(3), 000-000. www.ucr.ots.ac.cr www.ots.duke.edu.

Hillel D (1998) Environmental Soil Physics. Academic Press, London.

Hopkins B (1981) Forest and savanna. ELBS edition. Heinemann Educational Books Ltd Bath, Avon. UK.

Hurst DF, Griffith DWT and Cook GD (1994) Trace gas emissions from biomass in tropical Australian savannas. Journal of Geophysical Research 99 (D8): 16441-16456.

Hutley LB, O`Grady AP, Eamus D (2000) Monsoonal influences on evapotranspiration of savanna vegetation of northern Australia. Oecologia 126, 434-443.

IITA (1979) Selected methods for plant analyses (manual series No. 1 Revised edition). Juo, ASR (Editor) IITA, Ibadan, Nigeria.

Isichei A and Sanford RL (1980) Nitrogen loss by burning from Nigerian grassland ecosystem. In: Rosswall T (ed), Nitrogen Cycling in West Africa Ecosystems. Royal Swedish Academy of Sciences, Stockholm, 325-331.

Jansen D.H (1988) Tropical dry forest: the most endangered major tropical ecosystem. In: Wilson EC (ed), Biodiversity. National Academic Press, Washington, DC, 130-137.

Johnson EA (1992) Fire Vegetation dynamics: studies from the North America boreal forest. Cambridge University Press, Cambridge.

Johnston FH, Kavanagh AM, Bowman DMJS, and Scott RK (2002) Exposure to bushfire smoke and asthma: an ecological study. Medical Jornal of Australia 176, 535-538.

Justice CO, Kendall JD, Dowty PR and Scholes, RJ (1996) Satellite Remote Sensing of Fires during the SAFARI campaign using NOAA Advanced Very High Resolution Radiometer. Journal of Geophysical Research, 101, 23851-23863.

Kasei CN (1993) A synopsis on the climate of the north of Ghana. In: Proceedings: Workshop on improving farming systems in the interior savanna of Ghana. Nyankpala Agricultural Experimental Station (NAES), Nyankpala, Ghana.

Kasischke ES, French NHF, Harrell P, Christensen NL, Ustin SL and Barry D (1992) Monitoring of Wildfires in Boreal Using Large Area AVHRR NDVI Composite Image. http://cstars.ucdavis.edu/papers/sustin/borealf/paper.htm,

Kauffman JB, Sanford RL Jr, Cummings DL, Sacedo IH, and Sampaio EVSB (1993) Biomass and Nutrient dynamics associated with slash fires in neotropical dry forests. Ecology, 74 (1), 140-151.

Kauffman JB, Cummings DL and Ward DE (1994) Relationships of fire, biomass and nutrient dynamics along a vegetation gradient in the Brazilian cerrado. Journal of Ecology 82, 519-531.

Keenan T, Rutledge S, Carbone R, Wilson J, Takahashi T (2000) The Maritime Continent Thunderstorm Experiment (MCTEX): Overview and some results. Bulletin of the American Meteorological Society 81, 2433-2455.

Kellman M, Miyanishi K and Hieburt P (1985) Nutrient retention by ecosystems: 2. Retention after fire. J. Ecol. 73, 953-62.

Kent M and Coker P (2001) Vegetation Description and Vegetation Analysis, A Practical. Approach. Published by John Wiley and Sons Ltd., Baffins Lane, Chichester, England.

Ketterings QM, Bigham JM (2000) Soil color as an indicator of slash- and-burn fire severity and soil fertility in Sumatra, Indonesia. Soil Sci Soc Am J 64, 1826-1833.

Ketterings QM, Bigham JM, Laperche V. (2000) Changes in soil mineralogy and texture cuased by slash-and–burn fires in Sumatra, Indinesia. Soil Sci Soc Am J 64, 1108-1117.

Knapp AK, Conrad SL, Blair JM (1998) Determinants of soil CO_2 flux from a sub-humid grassland: effect of fire and fire history. Ecological Applications 8, 760-770

Knowels J (1993) The influence of forest-fire-induced albedo differences on the generation of mesoscale circulations. M.Sc. Thesis, Colorado State University, Fort Collins.

Korem A (1985) Bushfire and Agriculture Development in Ghana. Tema. Ghana Publishing Cooperation., 220.

Korem A (1989) Symposia Series (III) Revision of Ghana's Forest Policy. Land use, bushfires and the future of forest in Ghana, 132-139.

Koutsias N and Karteris M (1998) Logistic Regression Modelling of Multitemporal Thematic Mapper Data. International Journal of Remote Sensing., 19, 3499 – 3514.

Laclau J-P, Sama-Poumba W, de Dieu Nzila J, Bouillet J-P, Ranger J (2002) Biomass and nutrient dynamics in a littoral savanna subjected to annual fires in Congo. Acta Oecologica 23, 41 – 50.

Landon JR (ed), (1991) Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Booker Tate, Thame, Oxon, UK.

Lane DA (1962) The forest vegetation of Ghana. In: Willis JB 1962. Agricultural and landuse in Ghana. Ghana Ministry of Food and Agriculture, Oxford University Press, London, 451.

Langaas S (1993a) Diurnal Cycles in Savanna Fires. Nature; 363, 120-120.

Langaas S (1993b) Senegalese Fire Activity during the 1989-90. Dry Season Deduced from NOAA AVHRR Night Time Images. International Journal of Remote Sensing, 14, 2241-2244.

Langaas S (1995) Night-Time Observations of West Africa Bushfires from Space. Studies on Methods and Application of Thermal NOAA/AVHRR Satellite Data from Senegal and The Gambia. Thesis/Dissertation, Department of Geography, University of Oslo, Norway.

Laris P (2002) Burning the Seasonal Mosaic: Preventative Burning Strategies in the Wooded Savanna of Southern Mali. Human Ecology 30 (2).

Lawson GW (1985) Plant Life in West Africa. Ghana Universities Press, Accra.

Levine JS ed., (1991) Global Biomass Burning: atmospheric, climatic, and biospheric implications (Massachusetts: MIT Press)

Lewis LA and Berry L (1988) Africa Environments and Resources (Boston: Unwin Hyman).

Lewis WM (1974) Effects of fire on nutrient movement in a South Carolina pine forest. Ecology, 55; 1120-1127.

Lide DR (1998) CRC handbook of chemistry and physics: a ready-reference book of chemical and physical data. 79th ed. Boca Raton. CRC, 2556.

Lillesand TM and Kiefer RW (1994) Remote Sensing and Image Interpretation. John Wiley and Sons, 750.

Lillesand TM and Kiefer RW (2000) Remote Sensing and Image Interpretation. John Wiley and Sons, Inc. New York Chichester Weinheim Brisbane Singapore Toronto.

Little SN and Ohman J (1988) Estimating nitrogen loss from forest floor during prescribed fires in Doughlas-fir/Western hemlock clearcuts. For. Sci 34, 152-164.

Lynch AH and Wu WL (2000) impacts of fire and warming on ecosystem uptake in the boreal forest. Journal of Climate 13 (13), 2334 –2338.

Macadam A (1989) Effects of prescribed fire on forest soils. BC Ministry of Forests Research Report 89001-PR, Victoria

Mackensen J, Hölscher D, Klinge R and Fölster H (1996) Nutrient transfer to the atmosphere by burning of debris in eastern Amazonia. Forest Ecology and Management 86, 121 - 128.

Mallik AU, Gimingham CH, Rahman AA (1984) Ecological factors affecting heather burning: I, Water infiltration, moisture retention and porosity of surface soil. Journal of Ecology 72, 767-776.

Mathias AD, Fimbres A, Sano EE, Post DF, Accioly L, Batchily AK and Ferreira LG, (2000) Surface roughness effects on soil albedo. Soil Sci. Soc. Am. J. 64, 1035-1041.

Mbow C, Nielsen TT and Rasmussen K (1999) Savanna fires in east-central Senegal: Distribution patterns, resource management and perceptions. Submitted to Human Ecology.

Mearns LO, Schneider SL, Thompson SL and MacDaniel LR (1990) Analysis of climate variability in general circulation models: Comparison with observations and changes in variability in 2 x CO_2.

Menaut JC (1983) The vegetation of African Savannas. In: Bourliere F (ed.), Tropical savannas, Elservier. Amsterdam, 109-150.

Menaut JC, Abbadie L, Lavenu F, Loudjani P and Podaire A (1991) Biomass burninings in West African savannas. In: Levine JS (ed.), Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications, MIT Press, Cambridge Massachusets,132-142.

Menz M and Bethke M (2000) Vegetation map of Ghana. Regionalization of the IGBP Global Land Cover Map for Western Africa (Ghana, Togo and Benin). In: *Proceedings of the 20th EARSeL-Symposium*, June 2000, Dresden, in press. Remote Sensing Research Group. Institute of Geography. University of Bonn, Germany, 6.

Milich L and Weiss E (2000) GAC NDVI interannual coefficient of variation (CoV) images: ground truth sampling of the Sahel along north-south trasect International Journal of Remote Sensing.

Mills AJ and Fey MV (2004) Frequent fires intensify soil crusting: Physicochemical feedback in the pedoderm of long-term experiments in South Africa. Geoderma, 121 (1-2), 45-64.

Minnich RA (1983) Fire mosaics in Southern California and Northern Baja California. Science 219, 1287-1294.

Mintz Y (1984) The sensitivity of numerically simulated climates to land-surface boundary conditions, In: Houghton JT (ed), The Global Climate Change, edited by John T., Cambridge University Press, New York, 233.

Morgan JW (1999) Defining grassland fire events and the response of perennial plants to annual fire in temperate grassland of south-eastern Australia. Plant Ecology. 144, 127-144.

Mott JJ and Andrew MH (1985) The effect of fire on the population dynamics of native grasses in tropical savannas of north–east Australia. Proc. Ecol. Soc. Australia 13, 231-239.

Moyo CS, Frost PGH, Campbell BM (1998) Modification of soil nutrients and micro-climate by tree crowns in semi-arid rangeland of South-Western Zimbabwe. African Journal of Rangeland and Forage Science 15, 16-22

Nielsen, TT and Rasmussen K (1997) The distribution in time and space of savanna fires in Burkina Faso as determined from NOAA AVHRR Data. Danish Journal of Geography.

Noilhan J and Planton S (1989) A simple parametrization of land surface processes for meteorological models. Mon. Wea. Rev., 117, 536-549.

Nye PH and Stephens D (1962) Soil Fertility in Wills JG (ed) Agriculture and Land use in Ghana pp 127-143 Oxford University Press, London.

Oberdorfer E (1970) Pflanzensoziologische Strukturprobleme am Beispiel Kanarischer Pflanzengesellschaften. In: Tuxen R (ed.), Gesellschaftsmorphologie. Ber. Int. Symp. Int.Ver. Vegetationskunde, Stolzenau 1964. The Hague, Junk, 124 – 141.

O´Lear HA, Seastedt TR, Briggs JM, Blair JM, Ramundo RA (1996) Fire and topographic effects on decomposition rates and N dynamics of buried wood in tallgrass prairie. Soil Biology and Biochemistry 28, 323-329.

Olsson K (1985a) Desertification or Climate? Investigation regarding the relationship between land degradation and climate in central Sudan. Department of Geography, University of Luud, Sweden.

O´Neill Al, Head LM, Marthick JK (1993) Intergrating remote sensing and spatial analysis techniques to compare Aboriginal and pastorial fire patterns in the east Kimberly, Australia. Applied Geography 13, 67-85.

Owusu-Bennoah E, Acquaye DK and Abekoe M (1991) Efficient fertilizer use for increased crop production: Use of phosphorus fertilizers in concretional soils of Northern Ghana. In: Mokwunye AU (ed). Alleviating soil fertility constraints to increased crop production in West Africa 29 (1), 181-1194. Kluwer Academic Publishers.

Pan HL (1990) A simple parameterization scheme of evaptranspiration over land for the NMC medium-Range Forcast Model. Mon. Weather Rev., 118, 2500-2512.

Pereire AC, and AW Setzer (1993) Spectral Characteristics of Fire Scars in Landsat-5 images of Amazonia. International Journal of Remote Sensing, 14, 2061-2078. Robinson JM (1991). Problems in Global Fire Evaluation: Is Remote Sensing the Solution? In: Global Biomass Burning: Atmospheric, Climatic and biospheric implications, 67-73.

Philips JFV (1930) Fire: its influence on biotic communities and physical factors in South and East Africa. South African Journal of Science 27, 323-329.

Physick W and Tapper NJ (1990) A numerical study of circulations induced by a dry salt lake. Monthly Weather Review 118, 1029-1042.

Pikul JL and Zuzel JF (1994) Soil crusting and water infiltration affected by long –term tillage and residue Management. Soil Science Society of American Journal 58, 1524-1530.

Potter KN, Horton R, and Cruse RM, (1987) Soil surface roughness effects on radiation reflectance and soil heat flux. Soil Sci. Soc. Am.J.51, 855-860.

Prakash A and Gupta RP (1998) Land use mapping and change detection in a coal mining area. A case study in the Jharia coalfield, India. International Journal of Remote Sensing, 1998. 19 (3), 391-410.

Prins EM and Menzel WP (1992) Geostationry Satellite Detection of Biomass Burning in South America. International Journal of Remote Sensing 13, 16719-16735.

Puri AN and AG Asghar (1940) Physical characteristics of soils: VII. Effect of ignition. Soil Sci. 49, 369-378.

Pyne SJ, Andrews PL and Laven RD (1996) Introduction to Wildland Fire. John Wiley and sons, New York.

Raison R, (1979) Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review. Plant and Soil 51, 73-108.

Raison RJ, Khanna PK and Woods PV (1985a) Transfer of elements to the atmosphere during low-intensity prescribed fires in three Australia subalpine eucalypt forest. Can.J.For. Res. 15, 132-40.

Rasmussen MS (1998) Developing simple, operational, consistent NDVI- vegetation models by applying environmental and climatic information. Part: Assessment of Net Primary Production. International Journal of Remote Sensing, 19, 97-117.

Rawls WJ, Brakenseik DL and Saxton (1982) Estimation of soil water parameters. Trans. ASAE 25, 1316-1320.

Rejmanek M (1977) The concerpt of structure in phytosociology with reference to classification of plant communities. Vegetation 35, 55-61.

Robertson GP and Rosswall T (1986) Nitrogen in West Africa: The regional cycle. Ecology Monogr., 56, 43-72.

Robinson JM (1991)Fire from space: global fire evaluation using infrared remote sensing. International Journal of Remote Sensing 12 (1), 3-24.

Rogan J and Yool SR (2001) Mapping fire-induced vegetation depletion in the Peloncillo Mountains, Arizona and New Mexico. International Journal of Remote Sensing 22, 3101-3121.

Romas´ko VY, Kashkin VB, Sukhinin AN (2001) Post-fire inventory of forest based on satellite data: earth Observation and Remote Sensing 16, 991-996.

Rose Innes R (1977) A Manual of Ghana Grasses. Chatham: Natural Resources Institute.

Runge-Metzger A, Diehl L (1993) Farmhousehold systems in Northern Ghana. A case study in farming systems oriented research for the development of improved crop production systems. Nyankpala Agricultural Research Report No. 9.

Russell-Smith J, Ryan PG, Durieu (1997) A Landsat MSS-derived fire history of Kakadu national park, monsoonal northern Australia, 1980-94: seasonal extent, frequency and patchiness. Journal of Applied Ecology 34, 748-766.

Saarnak C.F. (1999) Trace Gas Emissions from Savanna Fires in West. Africa. Ph.D. Thesis. University of Copenhagen.

Saarnak CF Nielsen TT and Mbow C (1999c) Local study on the Trace Gas Emissions from Vegetation Burning Around the Village of Dalun-Ghana, with respect to Seasonal Vegetation Changes and Burning Practices. Climatic Change (In Press).

Salvador R, Valeriano J, Pons X, Diaz-Degado R (2000) A semi automated methodology to detect fire scars in shrubs and evergreen forest with Landsat MSS time series. International Journal of Remote Sensing 21, 655-671

San Jose JJ, Meirelles ML, Bracho R, and Nikonova (2001) A comparative analysis of flooding and fire effects on the energy exchange in a wetland community (Morichal) of the Orinoco Llanos. Journal of Hydrology 242, 228-254).

Savage MJ and Vermeulen K (1983) Micrclimate modification of tall moist grassland of Natal by spring burning: Journal of Range Management 36, 172-174

Schacht WH, Stubbendieck J, Bragg TB, Smart AJ, Doran JW (1996) Soil quality soil response of reestablished grasslands to mowing and burning. Journal of Range Management 49, 458-463.

Scholes RJ and Walter BH (1993) 'An African: Synthesis of Nylsvley Study.' Cambridge University Press UK.

Schowengerdt RA (1983) 'Techniques for image processing and classification in remote sensing.' Academic Press, New York.

Schroth G and Sinclair FL (2003) Trees, crops and soil fertility. Concepts and research methods. CABI Publishing, Wallingford, UK, 437.

Sertsu SM and PA Sanchez (1978) Effects of heating on some changes in soil properties in relating to an Ethiopian land management practice. Soil Sic. Soc. Am. J 42, 940-944.

Shea RW, Shea WS, Kauffman JB (1996) Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia Journal of geophysical research 101, D19, 23551-23568.

Smith DW and Bowes GC (1974) Loss of some elements in fly-ash during old-field burning in southern Ontario. Can. J. Soil Sci 54, 215-224.

Sommer R (2000) Water and nutrient balance in deep soils under shifting cultivation with and without burning in the Eastern Amazon. Ph.D Thesis. University of Göttingen.

Sreenivasan A and RK Aurangabadkar (1940) Effect of fire heating on the properties of black cotton soils in comparison with those of gray and of humus treated soils. Soil Sci. 51, 449-462.

SRI (2001) Soil map of Ghana. Soil Research Institute, Accra, Ghana

Stemmler J and Su Z (1993) In: Su Z Remote sensing of land use and vegetation for mesoscale hydrological studies. International Journal of Remote Sensing, 21 (2), 213-233.

Stoorvogel JJ and Smaling EME (1990) Assessment of soil nutrient depletion of sub-Saharan Africa. Wageningen, NL: The Winand Staring Centre (Report 28, Vols I-IV).

Stott P (1991) Recent trends in the ecology and management of the world's savanna formations. Progress in Physical Geography, 15, 18-28.

Stott P (1994) Savanna landscapes and global environmental change. In: Roberts N (ed), The Changing Global Environment, Blackwell, Cambridge, 287-303.

Sunar F (1998) An analysis of changes in a multi-date data set: a case study in the Ikitelli area, Istanbul, Turkey International Journal of Remote Sensing 21 (2), 213-233

Tapper N (1991) Evidence for mesoscale themal circulation over dry salt lakes. Palaeoclimatology, Palaeoecology 84, 259-269.

Taylor CJ (1952) The vegetation zones of the Gold Coast, Government Printer Forestry Dept. Bull. Accra, (4), 271.

Tiedeman AR, Klemmedson JO, Bull EL (2000) Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk? For Ecol. Manag. 127, 1-18

Tooming H (2002) Dependence of global radiation on cloudiness and surface albedo in Tatu, Estonia. Theoret. Appl. Climatol. 72, 165-172.

Trabaud L (1994) The effect of fire on nutrient losses and in a Quercus coccifera garrique (Southern France). Oecologia 99, 379-386.

Trollope WSW, LA Potgeiter, ALF and Zambatis N (1996) SAFARI-92 Characterization of Biomass and Fire Behaviour in the small Experiment Burns in the Kruger National Park. Journal of Geophysical Research, 101, 23531-23539.

Trigg S, Flasse S (2000) Characterizing the spectral-temporal response of burned savannah using in-situ spectroradiometry and infrared thermometry. International Journal of Remote Sensing 21, 3161-3168.

Trotter CM (1998) Characterizing the topographic effect at red wavelengths using juvenile conifer canopies. International Journal of Remote Sensing 19 (11), 2215-2221.

Turner MG, Hargrove WW, Gardner RH, Romme WH (1994) Effects of fire on landscape heterogeneity in Yellowstone National-Park, Wyoming. Journal of Vegetation Science 5, 731-742.

Turner CL, Blair JM, Schartz RJ, Neel JC (1997) Soil N and plant responses to fire, topography and supplemental N in tallgrass prairie. Ecology 78, 1832-1843.

Tüxen, R (ed) (1970a) Gesellschaftsmorphologie. Ber. Int. Symp. Int. Ver. Vegetationskunde, Rinteln 1966. The Hague, Junk.

Ulery AL and Graham RC (1993) Forest fire effects on soil colour and texture. Soil science society of American Journal 57.

Ulery AL, Graham RC, Amrhein C (1996) Forest fire effects on phyllosilicates. Soil Sci. Am. J 60, 306-315.

Viedma O, Melia J, Segarra D, Garciaharo J (1997) Modeling rates of ecosystem recovery after fires by using Landsat-TM data. Remote Sensing Environment 61, 383-398.

Vijver van de C (1999) Life and Fire in the Tarangire: Effects of Burning and Herbivory on an East Africa Savanna System. Ph.D. Thesis. Wageningen Agricultural University.

Vlek PLG (1993) Strategies for sustaining agriculture in sub-Saharan Africa: the fertilizer technology issue. In: Madison, WI (ed), Technologies for sustainable agriculture in the tropics ASA. CSSA, SSSA, USA, 265-277.

Walker BH and Noy-Meir, I (1982) Aspect of stability and resilience of savanna ecosystem. In: Huntley BJ and Walker BH (ed), Ecology of tropical Savannas, Springer-Verlag, New York, 556-590.

Walker J, Raison RJ, Khanna PK (1986) The impact of fire on Australia soils. In: Russell JS and Isbell (eds), The impact of man on Australia soils. University of Queensland Press, St. Lucia, Queensland, Australia.

Weast RC (1980) Handbook of chemistry and physics. 60th ed. CRC Press, Inc. Boca Raton, Florida.

Wells CG, Campbell RE, DeBano LF, Lewis CE, Fredriksen RL, Ranklin EC, Froelich RC and Dunn PH (1979) Effects of fire on soil. U. S. For. Serv. Gen. Tech. Rep. Wo-7. U. S. For. Serv., Washington, DC.

Werger MJA (1973b) Phytosociology of the Upper Orange Valley, South Africa. PhD Thesis, Univ. V & R., Nijmegen, Pretoria.

West O (1965) Fire in vegetation and its use in pasture management with special reference to tropical and subtropical Africa. Commonwealth Agricultural Bureaux. Farnham Royal, Bucks, UK, Mimeographed publication (1).

Westhoff V (1967) The problems and use of structure in the classification. Acta bot. Neerl. 15, 495-511.

Westhoff V (1968) Einige Bemerkungen zur syntaxonomischen Terminologie and Methodik, insbessondere zu der Struktur als dignostischem Merkmale. In R. Tüxen (ed) Pflanzensoziologische Systematik. Ber. Int. Symp.Int. Ver. Vegetationskunde, Stolzenau 1964. The Hague, Junk, 54-70.

Whelan RJ (1995) The ecology of fire. Cambridge University Press, Cambridge.

White EM, Thompson WW and Gartner FR (1973) Heat effects on nutrient release from soils under Ponderrosa pine. Journal of Range Management. 26, 22-24.

Wills JB (1962) Agriculture and land use in Ghana. Ghana Ministry of Food and Agriculture. Oxford University Press, London.

Williams RJ, Myers BA, Muller WA, Duff GA and Eamus D (1997) Leaf phenology of woody species in a northern Australian tropical savanna. Ecology 78, 2442-2558.

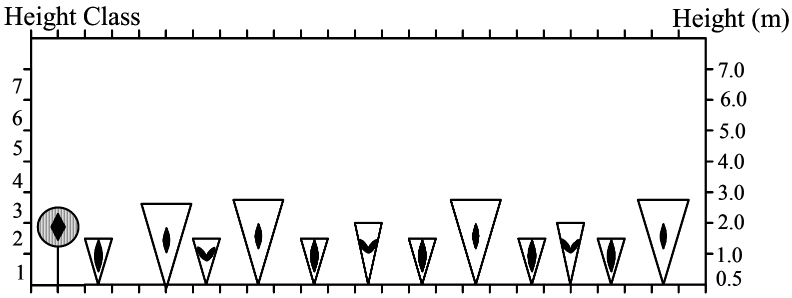
Wilson BA, Russell-Smith J, Williams RJ (1995) Terrestrial vegetation. In: Finlay CM and von Oertzen I (eds), Landscape and Vegetation Ecology of the Kakadu Region, Northern Australia. Kluwer Academic Publishers, Dordrecht.

Wooster MJ (2001) Remote sensing of vegetation fires. Department of Geography, King's college London.

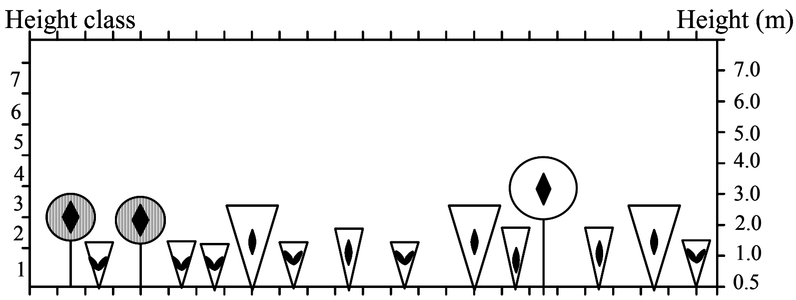
Yin X (1998) The albedo of vegetated land surfaces: Systems analysis and mathematical modeling. Theoret. Appl. Climatol. 60, 121-140.

8 APPENDIX

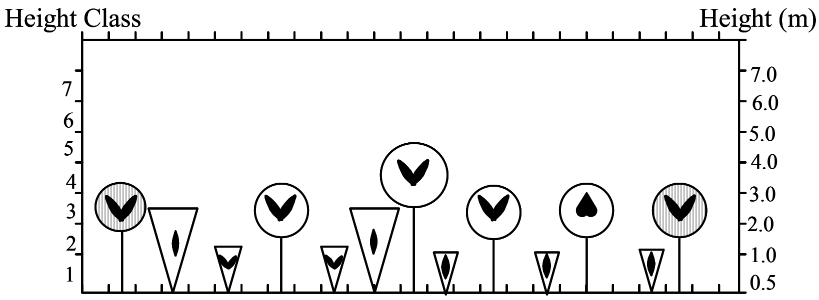
Below are profile diagrams with their respective codes of all the sites sampled in the study area.



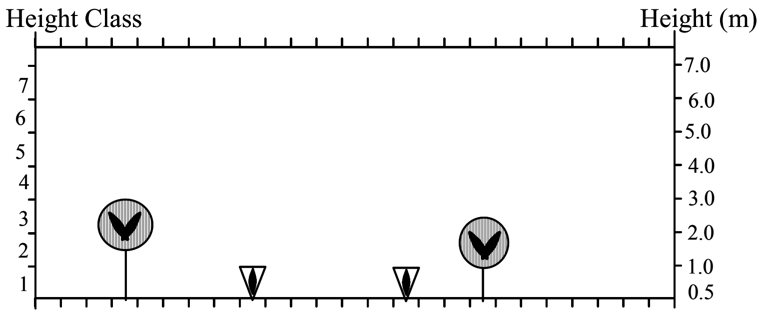
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Sambu). W4saxb, H3dg(v)xc, H2dgxc (Structural codes according to Dansereau, 1958).



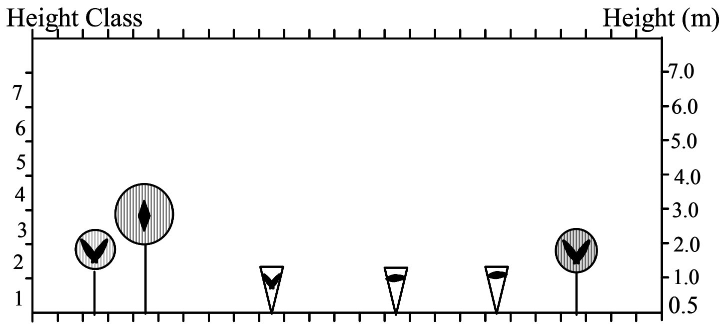
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Salkpang). W4daxb, W3saxb, H3dgxp, H2dv(g)xc (Structural codes according to Dansereau, 1958).



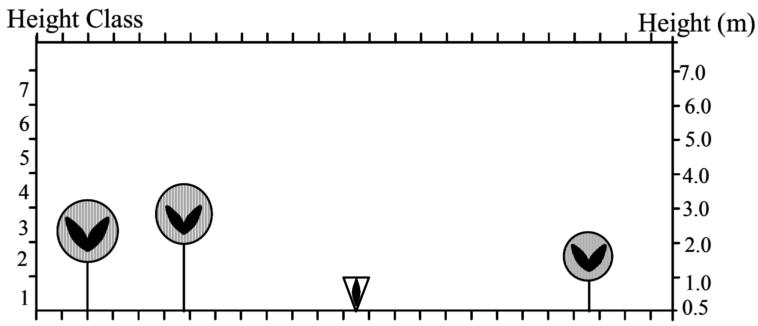
Structural diagram of open savanna woodland dominated by shrubs (close to Jimle).
W4d(s)vxi,W3dvxp, H3dgxp, H2dg(v)xc (Structural codes according to Dansereau, 1958).



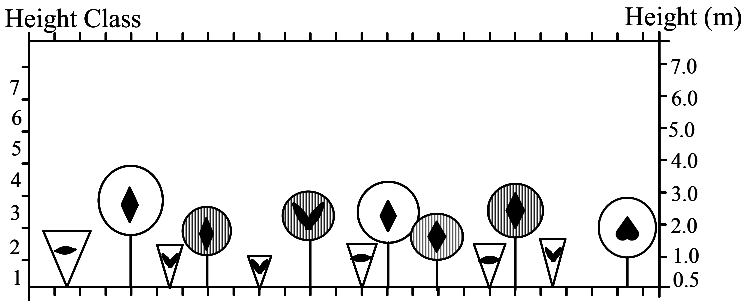
Structural diagram of widely open savanna woodland (close Juni) W4svxp, W3svxp, H2dgxb (Structural codes according to Dansereau, 1958)



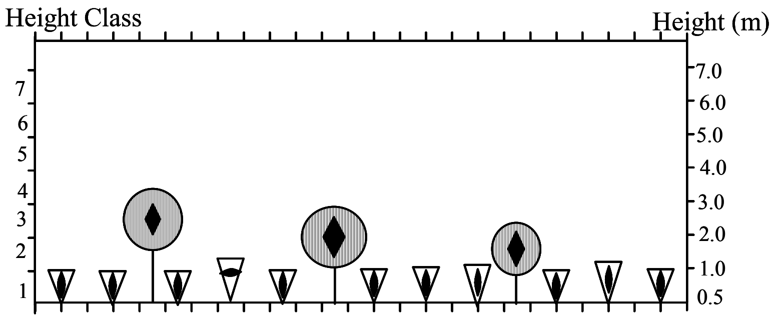
Structural diagram of widely open savanna woodland (close to Juni) W4saxi, W3sx(a)p, H3dn(v)i (Structural codes according to Dansereau, 1958)



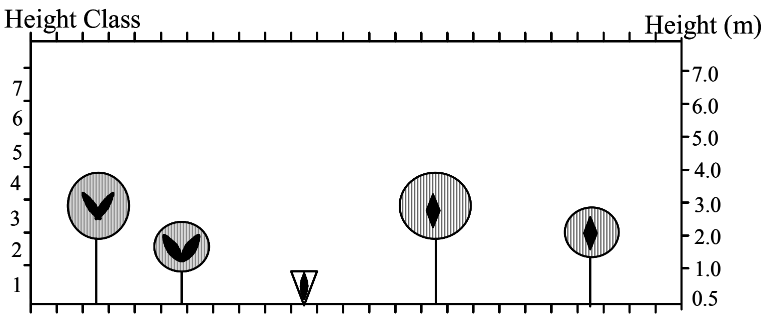
Structural diagram of widely open savanna woodland (close to Sabonjida) W4svxp, W3svxp, H3dgxb (Structural codes according to Dansereau, 1958)



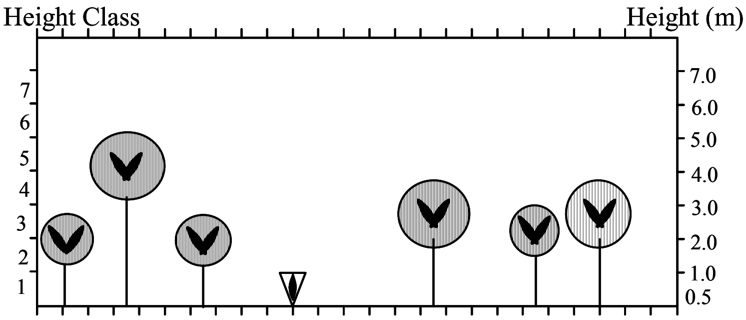
Structural diagram of open savanna woodland dominated by shrubs (close to Jagbajado). W5saxi, W4svxi, H3dn(v)c, H2dn(v)c (Structural codes according to Dansereau, 1958).



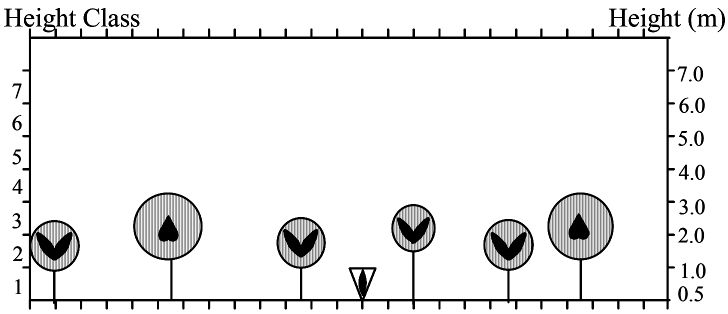
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Nyamaliga). W4saxi,W3saxi, H2dg(n)I (Structural codes according to Dansereau, 1958).



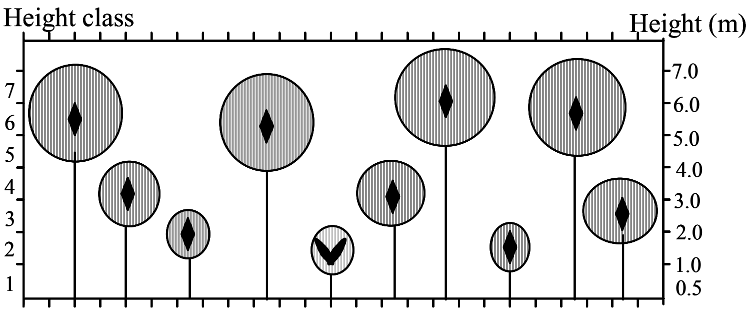
Structural diagram of widely open savanna woodland (close to Gbung) W5sa(v)xb,W4sa(v)xi, H1dgxb (Structural codes according to Dansereau, 1958)



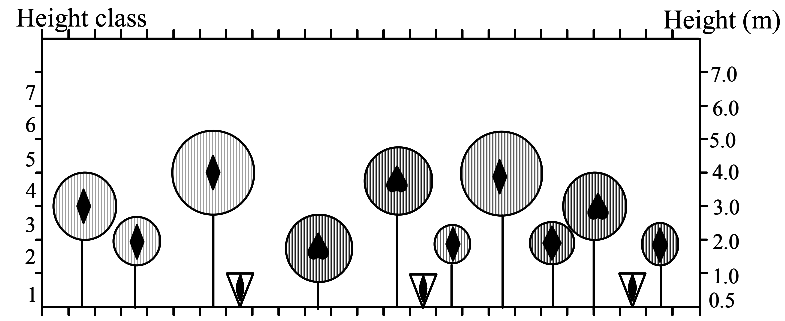
Structural diagram of widely open savanna woodland (close to Kpalbusi) W6svxb,W4svxp,H1dgxb (Structural codes according to Dansereau, 1958)



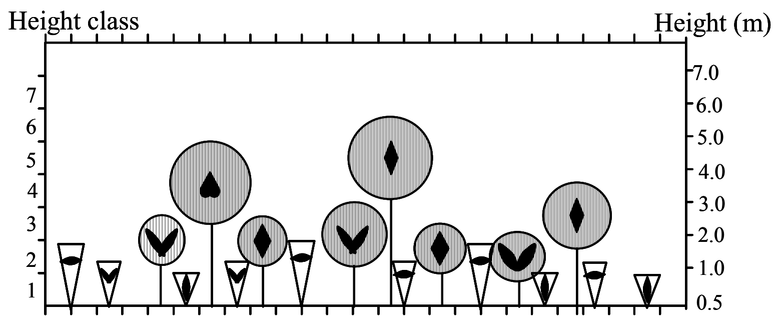
Structural diagram of widely open savanna woodland (close to Massaka) W4sv(h)xi,W3sv(v)xc,H1dgxb (Structural codes according to Dansereau, 1958)



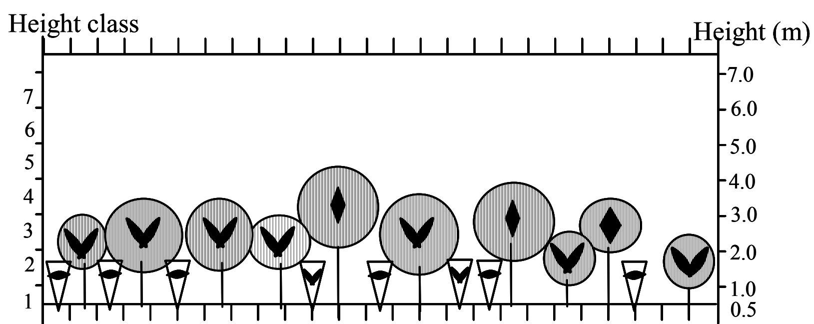
Structural diagram of closed savanna woodland dominated (close to Alhassan-Kura) W7saxi, W5saxi, W2sa(v)b (Structural codes according to Dansereau, 1958)



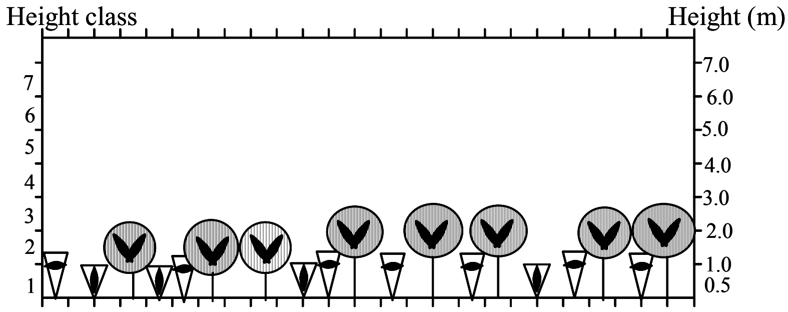
Structural diagram of closed savanna woodland dominated (close to Dagomba-Line) W6sa(h)xi, W5sa(h)xi, W4sa(h)xi, H2dgxb (Structural codes according to Dansereau, 1958)



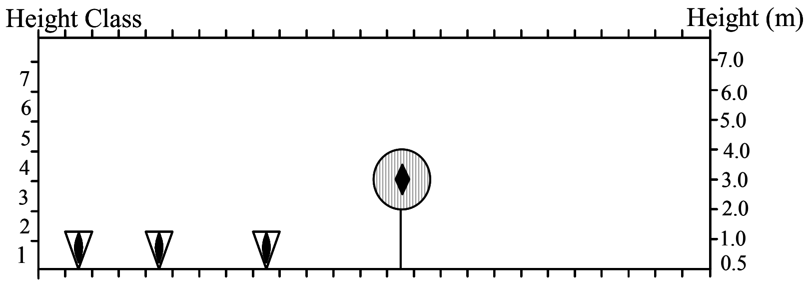
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Sarikyekura). W6sa(h)xi,W4sa(v)xi,H3sa(v)xi (Structural codes according to Dansereau, 1958).



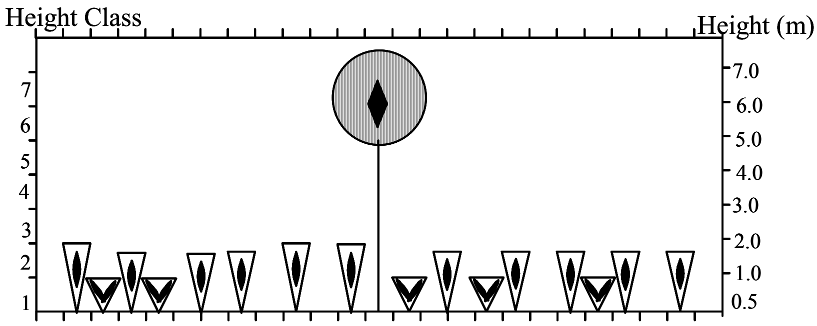
Structural diagram of open savanna woodland dominated by shrubs (close to Ntreso). W4saxi,W3sv(a)xc, H2dn(v)xi (Structural codes according to Dansereau, 1958).



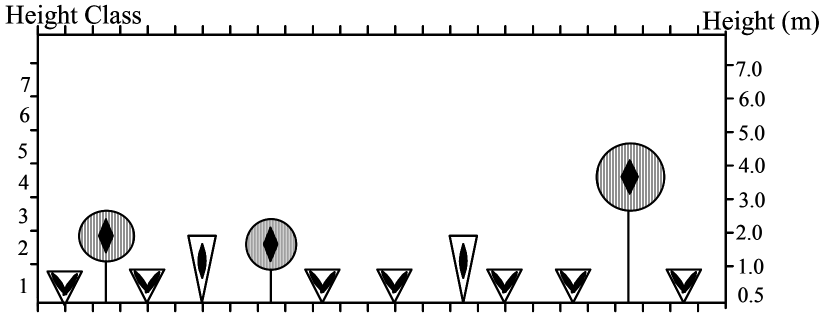
Structural diagram of open savanna woodland dominated by shrubs (close to Jerimoape). W3svxi, H2dn(g)xc (Structural codes according to Dansereau, 1958).



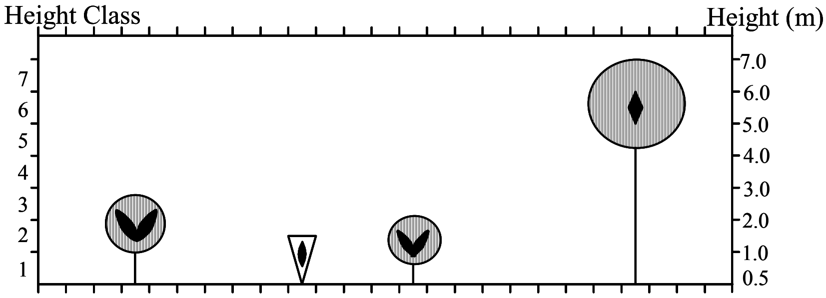
Structural diagram of widely open savanna woodland (close to Grupe) W5saxb,H2dgxi (Structural codes according to Dansereau, 1958)



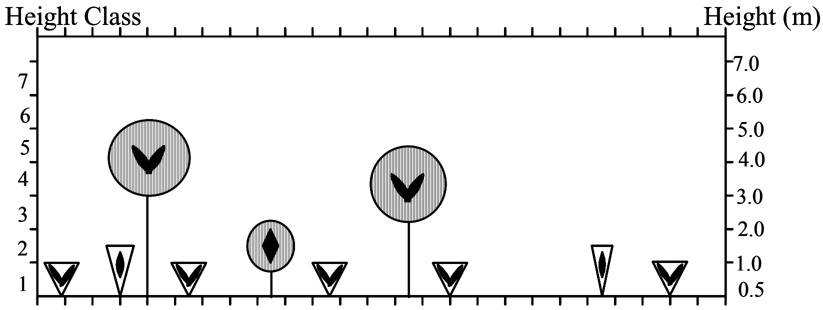
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Kanantu). W7saxi, H2dg(v)xc (Structural codes according to Dansereau, 1958).



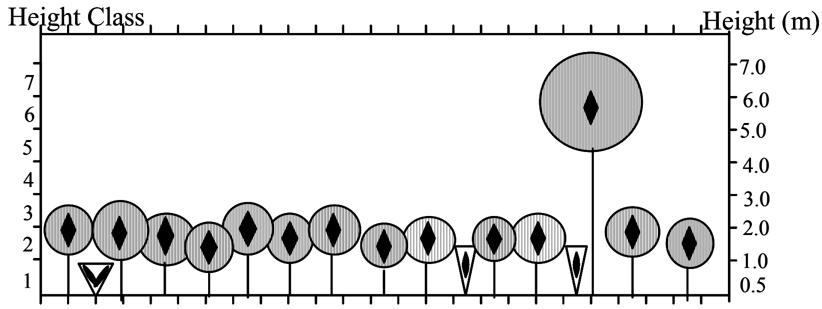
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Larabanga). W6saxb,W4saxi,H3dgxc,H2dvxc (Structural codes according to Dansereau, 1958).



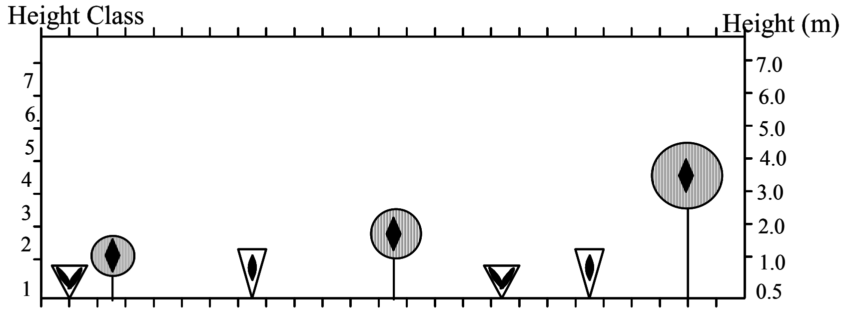
Structural diagram of widely open savanna woodland (close Damongo) W7saxi,W3svxi,H2dgxb (Structural codes according to Dansereau, 1958)



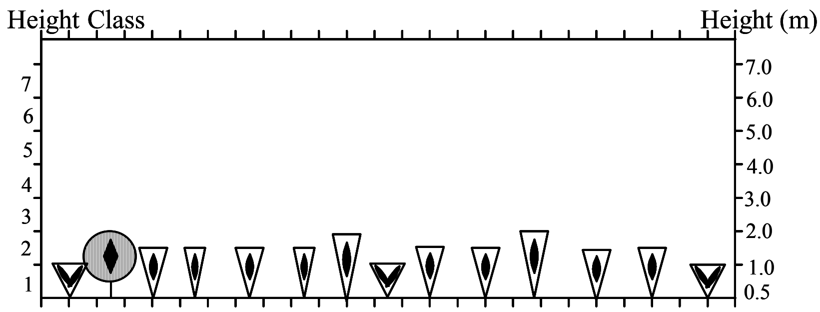
Structural diagram of widely open savanna woodland (close Joronokponto) W6saxi,W2saxb,H2dv(g)xp (Structural codes according to Dansereau, 1958)



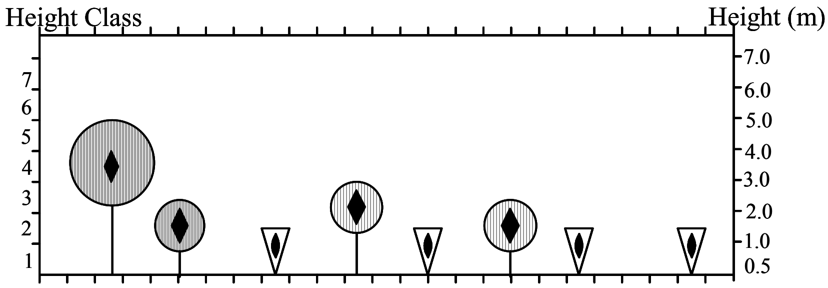
Structural diagram of open savanna woodland dominated by shrubs (close to Gurugu). W7saxb,W3saxc,H2dg(v)xb (Structural codes according to Dansereau, 1958).



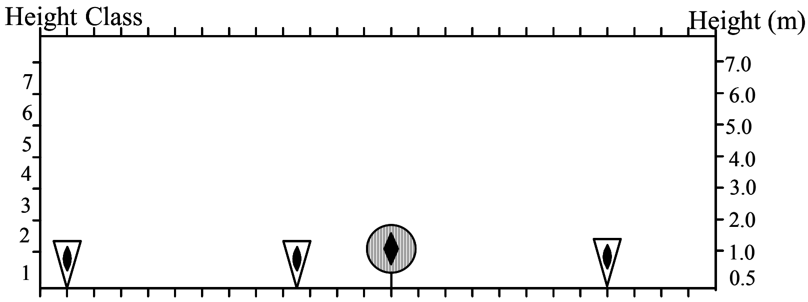
Structural diagram of widely open savanna woodland (close Sinsini) W6saxb,W3saxb,H2dv(g)b (Structural codes according to Dansereau, 1958)



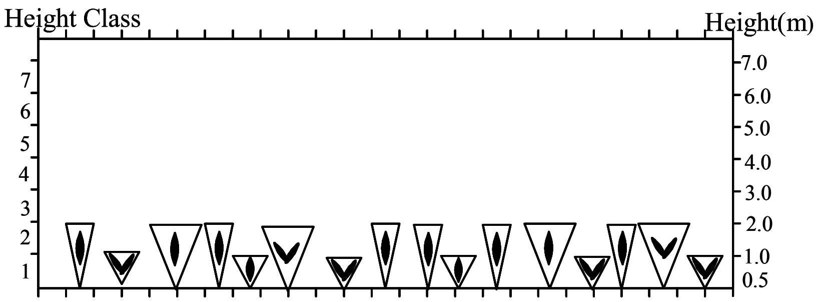
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Nanton). W2saxb,H3dg(v)xc,H2dg(v)c (Structural codes according to Dansereau, 1958).



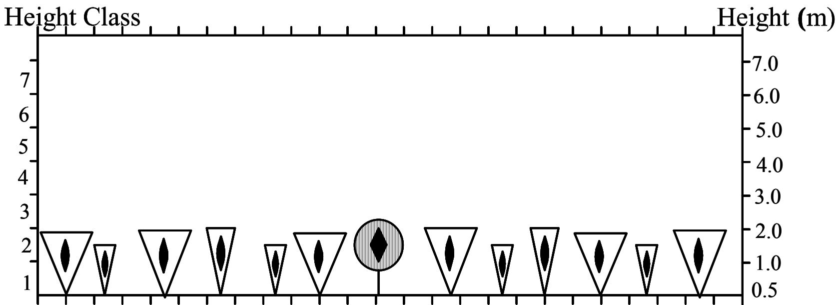
Structural diagram of widely open savanna woodland (close Zinindo) W6saxi,W3saxi, H2dgxp(Structural codes according to Dansereau, 1958)



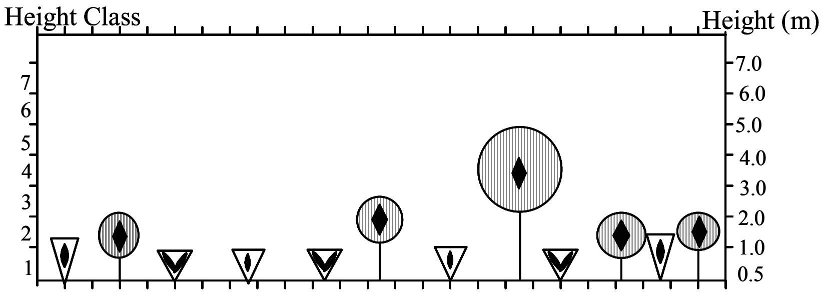
Structural diagram of widely open savanna woodland (near Gaa) W3saxb,H2dgxi
(Structural codes according to Dansereau, 1958)



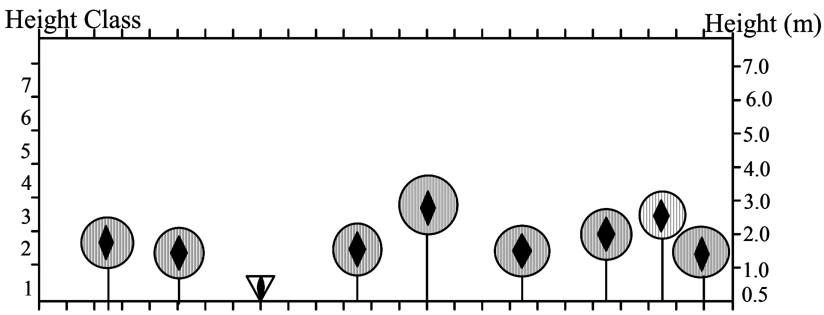
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to Kpandain). H3dg(v)xc,H2dg(v)xc
(Structural codes according to Dansereau, 1958).



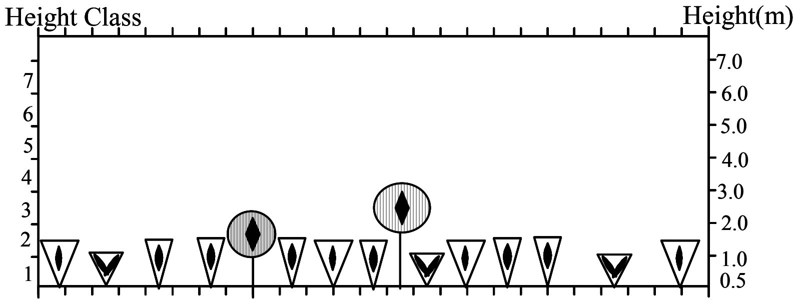
Structural diagram of grass/herb fallow with scattered trees and shrubs (close to near Nakoli). W3saxb, H3dgxc (Structural codes according to Dansereau, 1958).



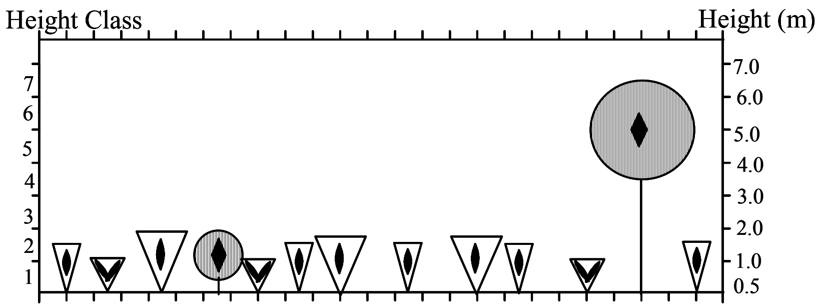
Structural diagram of widely open savanna woodland (near Gbambu) W6saxb,W3saxp,H2dg(v)xp (Structural codes according to Dansereau, 1958)



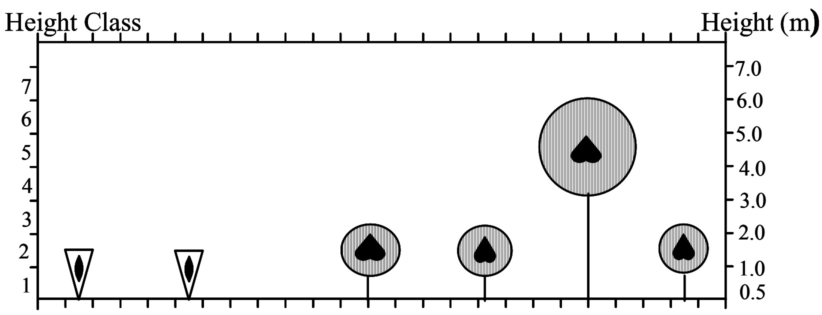
Structural diagram of widely open savanna woodland (near Nasuan) W3saxp,W2saxp,H1dgxb (Structural codes according to Dansereau, 1958)



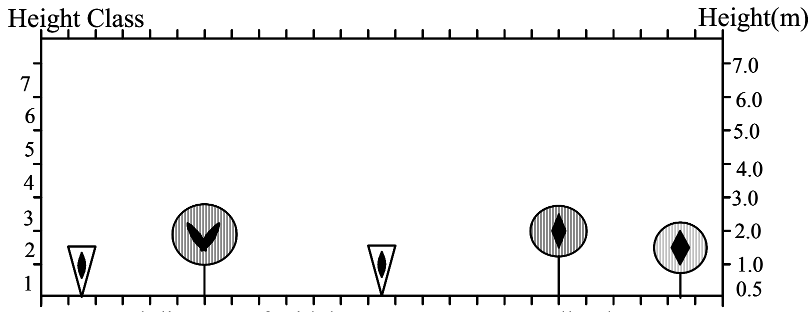
Structural diagram of grass/herb fallow with scattered trees and shrubs (near Janga). W4saxb,W3saxb,H2dg(v)xp
(Structural codes according to Dansereau, 1958).



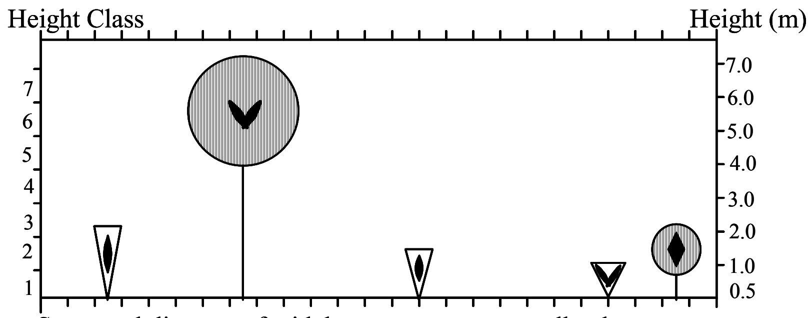
Structural diagram of grass/herb fallow with scattered trees and shrubs (near Kadia). W6saxb,W2saxb,H2dg(v)xp
(Structural codes according to Dansereau, 1958).



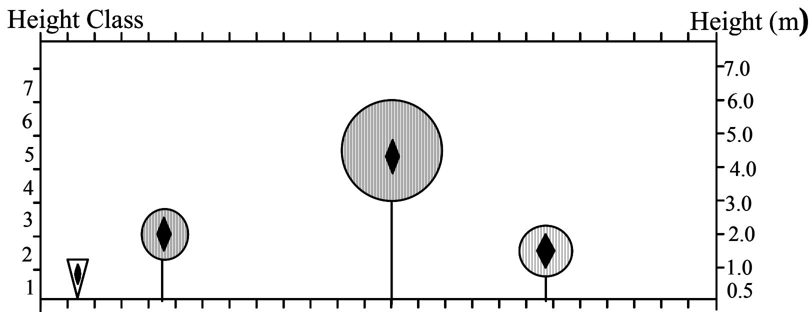
Structural diagram of widely open savanna woodland
(close to Kukobila) W6shxb,W2shxi,H2dgxi
(Structural codes according to Dansereau, 1958)



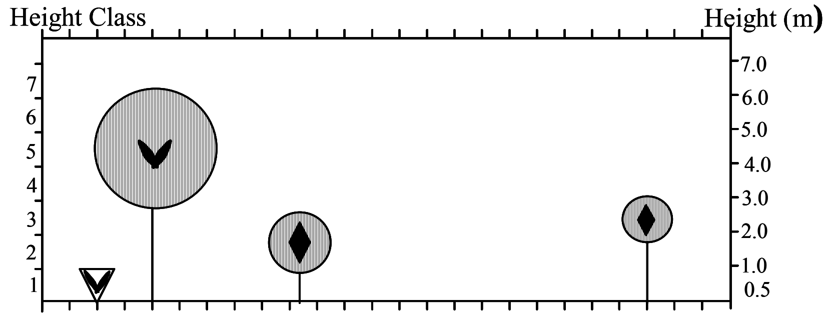
Structural diagram of widely open savanna woodland
(near Nabogu) W3sv(a)xi, H3dgxi
(Structural codes according to Dansereau, 1958)



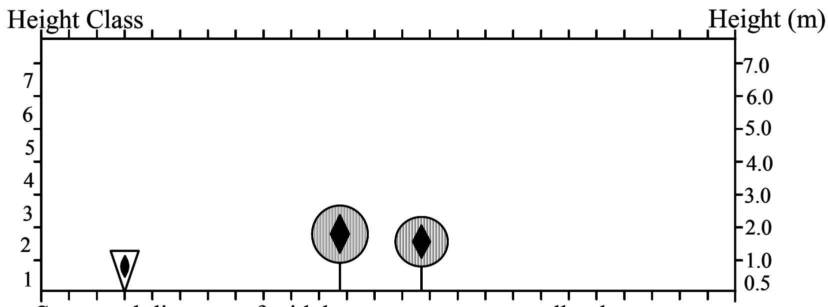
Structural diagram of widely open savanna woodland
(close to Loagri) W7svxb,W3saxb, H3dgxi,H2dvxi
(Structural codes according to Dansereau, 1958)



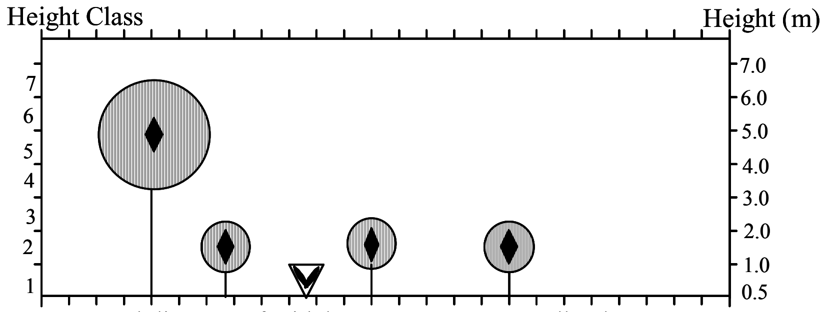
Structural diagram of widely open savanna woodland
(near Gbimsi) W6saxb,W4saxb,W3saxb,H1dgxb
(Structural codes according to Dansereau, 1958)



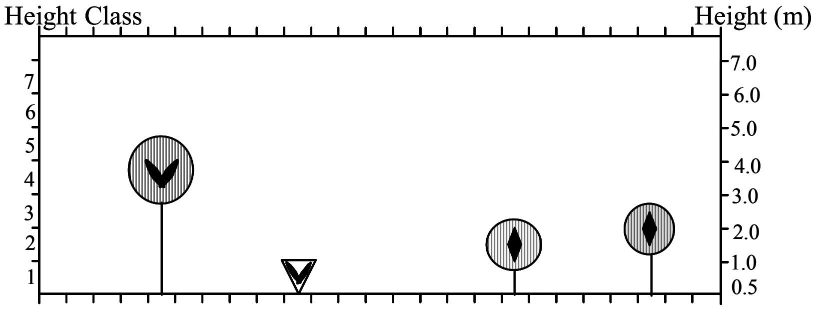
Structural diagram of widely open savanna woodland
(near Karamenga) W6svxb,W4saxb,W3saxb,H2dvxb
(Structural codes according to Dansereau, 1958)



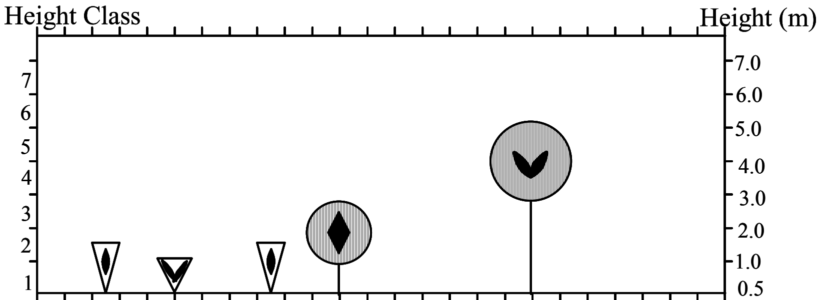
Structural diagram of widely open savanna woodland
(near Timpella) W3saxb,H2dgxb
(Structural codes according to Dansereau, 1958)



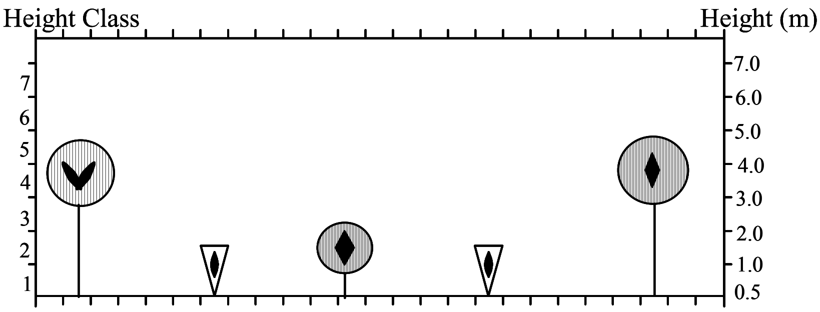
Structural diagram of widely open savanna woodland
(close to Sadugu) W7saxb,W3saxb,H2dvxb
(Structural codes according to Dansereau, 1958)



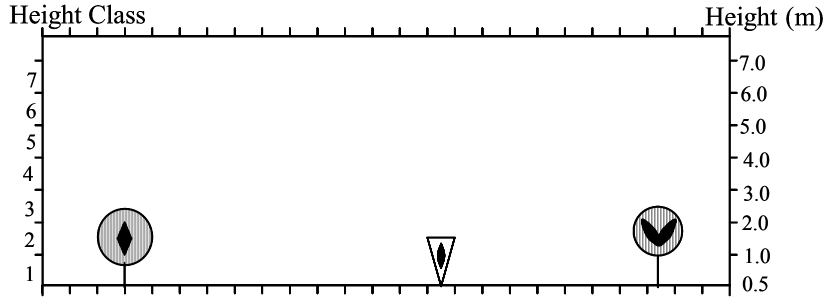
Structural diagram of widely open savanna woodland
(close to Daboyiri) W6svxb,W3saxb,H2dvxb
(Structural codes according to Dansereau, 1958)



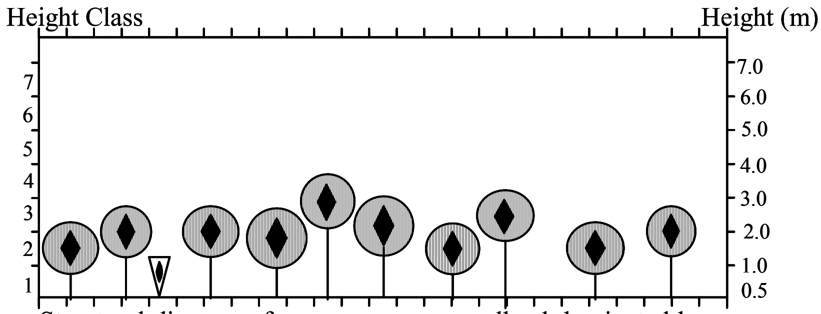
Structural diagram of widely open savanna woodland
(close to Bole) W6svxb,W3saxb,H3dgxb,H2dvxb
(Structural codes according to Dansereau, 1958)



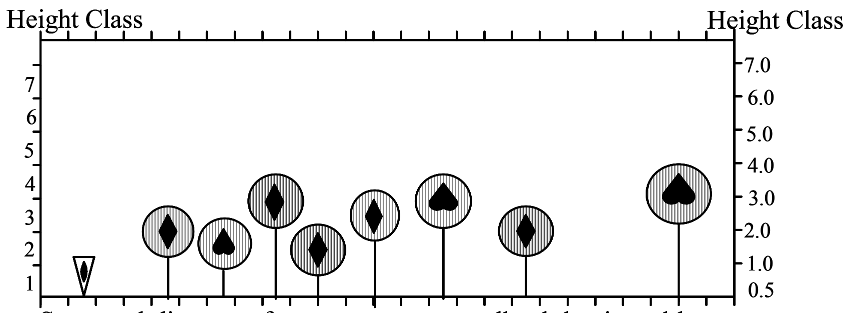
Structural diagram of widely open savanna woodland
(near Lampoga) W6sa(v)xi,W3saxb, H2dgxb
(Structural codes according to Dansereau, 1958)



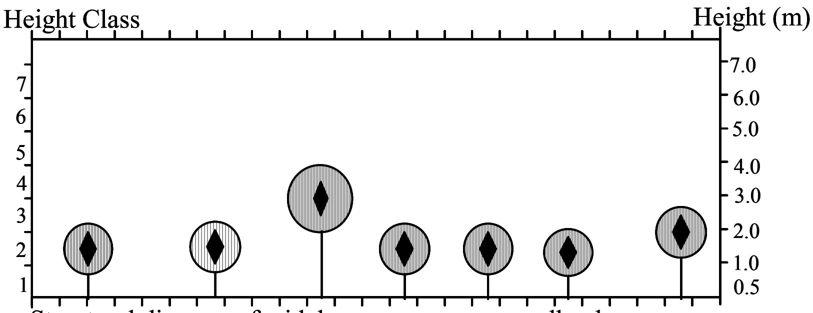
Structural diagram of widely open savanna woodland (near Pishiegu) W3sa(v)xb,H2dgxb (Structural codes according to Dansereau, 1958)



Structural diagram of open savanna woodland dominated by shrubs (close to Nyong). W3saxp,W2saxp,H2dgxb (Structural codes according to Dansereau, 1958).



Structural diagram of open savanna woodland dominated by shrubs (close to Tamaligu). W4sa(h)xp,W3sa(h)xp,H2dgxb (Structural codes according to Dansereau, 1958).



Structural diagram of widely open savanna woodland
(close to Bontanga) W5saxb,W3saxp
(Structural codes according to Dansereau, 1958)

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