Zentrum für Entwicklungsforschung

Spatio-temporal dynamics of bush-fire nutrient losses and atmospheric depositional gains across the northern savanna region of Ghana

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ABSTRACT

This study estimates the nutrient balance between annual fire-induced nutrient transfers and bulk (wet plus dry) atmospheric nutrient deposition. In the subsistence-based and fertilizer-limited agriculture of northern Ghana the population depends on productivity of the native soils for crop production. Fifty three percent of this region is burned annually. This study quantifies the nutrient losses resulting from the annual fires as well as the nutrient acquisition through atmospheric deposition which may compensate for the losses. A quantification of the soil-atmosphere nutrient cycling would help policy-makers in setting incentives and disincentives to regulate the burning culture of the region.

Gross seasonal and annual elemental-losses/gaseous-emissions were quantified in the field for each combusted vegetation type. Annual spatial/temporal wet and dry deposition samples were collected across 15 sites. Data were analysed by a variety of analytical techniques including descriptive statistics, time series analyses, pairwise t-testing, ANOVA, linear correlations, linear regression, remote sensing and GIS. The field measurements of elemental-losses/gaseous-emissions and nutrient-depositions combined with the temporal-geospatial dynamics of these processes were analysed by various statistical means and extrapolated to the entire region using 10-year (2001-2010) GIS/remote sensing data.

The results show that combusted fuel load varies across different vegetation types by season of burn and by plant tissue, with highest combustion taking place in the herbaceous/grass tissues. Lower combustion of twigs suggests a safe storage of carbon (C) in the woody parts of plants. In the early-burn season (November) high tissue-nitrogen (N) concentration renders burns vulnerable to high N losses/emissions per unit burnt biomass. However, high tissue moisture impedes the early burns, resulting in patches of burned and unburned vegetation that reduce the occurrence of late burns and the total losses of plant-nutrients. The patches of unburned vegetation also enhances tree seedling establishment to ages when these are relatively resistant to fires. The magnitude of gaseous emissions and nutrient losses follows the monthly order December>November>January>February. Calcium (Ca) and Magnesium (Mg) are lost in particulate forms, phosphorus (P) and potassium (K) in both, particulate and non-particulate forms, whereas C and N are mostly lost in gaseous forms.

Dry and wet nutrient deposition varied with latitude and month. The interaction of latitude and longitude on nutrient deposition suggests that fire-induced nutrient transfers are directed by atmospheric currents (northeast to southwest) at the time of burn. An estimated negative N balance is not a cause for concern, as most N losses could be replaced through biological N_2-fixation. Positive balances for K, Ca, Mg and sodium (Na) indicate an external source for these nutrients besides the redistribution of nutrients originating from fires, possibly Saharan dust. A net negative balance for P (-18 to -1 Gg), however, should be of major concern across the region given the inherently low P-content of the soils and the inability to derive P from other sources. The negative P balance poses a serious challenge to future food production across the area. Phosphorus losses can however be reduced when burning is undertaken in the early dry-season.

Räumlich-zeitliche Dynamik von durch Buschfeuer verursachten Nährstoffverlusten und atmosphärischen Einträgen in der nördlichen Savannenregion Ghanas

KURZFASSUNG

Der Schwerpunkt dieser Studie ist die Ermittlung der Nährstoffbilanz zwischen dem jährlich durch Vegetationsbrände verursachten Gesamtnährstofftransfer und der Gesamtmasse (nasse und trockene) der atmosphärischen Nährstoffeinträge. In der subsistenzbasierten Landwirtschaft Nordghanas, die nur wenige Düngemittel zur Verfügung hat, ist die Bevölkerung von der Produktivität der Böden für den landwirtschaftlichen Anbau abhängig. 53% der Fläche Nordghanas verbrennt jährlich. Diese Studie quanitifiziert die durch die jährlichen Feuer verursachten Nährstoffverluste ebenso wie die Rückgewinnung von Nährstoffen durch atmosphärische Deposition, welche die Verluste kompensieren könnte. Eine Quantifizierung der zwischen Boden und Atmosphäre zirkulierenden Nährstoffe würde Entscheidungsträgern helfen, positive und negative Anreize zu schaffen, um die Verbrennungs-Kultur der Region zu regulieren.

Die jahreszeitlichen und jährlichen Bruttoverluste und Emissionen von ausgewählten Elementen wurden im Feld für jeden verbrannten Vegetationstyp bestimmt. Proben von jährlichen räumlichen/zeitlichen nassen und trockenen Einträgen wurden an 15 Standorten genommen. Die Daten wurden durch mehrere Verfahren analysiert, d.h. beschreibende Statistik, Zeitreihenanalysen, paarweiser t-Test, ANOVA, lineare Korrelation, lineare Regression, Fernerkundung und GIS. Die Freilandmessungen der Nährstoffverluste/ der gasförmigen Emissionen und Nährstoffeinträge wurden in Zusammenhang mit den räumlich-zeitlichen Dynamiken dieser Prozesse anhand verschiedener statistischer Verfahren analysiert und mit Hilfe von GIS/Fernerkungungsdaten von 2001 bis 2010 auf die gesamte Region extrapoliert.

Die Ergebnisse zeigen, dass die Menge der verbrannten Biomasse in den verschiedenen Vegetationstypen abhängig von der Jahreszeit der Brände und vom Pflanzengewebe ist, wobei der höchste Verbrennungsgrad bei krautigem/Grasgewebe beobachtet wurde. Ein niedrigerer Verbrennungsgrad bei Zweigen deutet auf eine sichere Speicherung von Kohlenstoff (C) in den verholzten Teilen der Pflanzen hin. In der frühen Feuersaison (November) führt die hohe Gewebe-Stickstoff (N)-Konzentration zu einer Anfälligkeit der Brände für hohe N-Verluste/ Emissionen pro Einheit verbrannter Biomasse. Jedoch behindert hier die hohe Gewebefeuchtigkeit die Ausbreitung der frühen Brände. Dies führt zu Flächen von abwechselnd verbrannter sowie nichtverbrannter Vegetation, welches das Auftreten später Brände und die Brutto-Verluste von Pflanzenznährstoffen reduziert. Die unverbrannten Flächen fördern zudem die Entwicklung von Baumkeimlingen bis zu einem Alter, in dem die Bäume verhältnismäßig feuerresistent sind. Die Größe der verbrannten Vegetationsflächen, die Menge der gasförmigen Emissionen und die Nährstoffverluste sinken in der monatlichen Reihenfolge Dezember>November>Januar>Februar. Verluste von Calcium (Ca) und Magnesium (Mg) sind partikelförmig, Phosphor (P) und Kalium (K) sowohl partikelförmig als auch gasförmig, während C- und N-Verluste überwiegend gasförmig sind.

Breitengrad und Monat hatten die größte Auswirkung auf die nassen und trockenen Nährstoffeinträge. Die Interaktion zwischen Breitengrad und Längengrad auf den Nährstoffeintrag deutet darauf hin, dass die durch Feuer verursachten Nährstoffverfrachtungen von den atmosphärischen Strömungen (Nordost nach Südwest) zum Zeitpunkt der Brände beeinflusst werden. Eine negative N-Bilanz ist nicht besorgniserregend, da die meisten N-Verluste durch biologische N_2-Fixierungsprozesse ausgeglichen werden können. Die positive Bilanz für K, Ca, Mg und Natrium (Na) deutet auf eine externe Quelle für diese Nährstoffe zusätzlich zu der Verteilung durch Brände hin, vermutlich Staub aus der Sahara. Die negative Nettobilanz für P (-18 bis -1 Gg) sollte jedoch Anlass zur Sorge sein, wenn man den von Natur aus geringen P-Gehalt der Böden berücksichtigt, sowie die Unmöglichkeit, P aus anderen Quellen zu gewinnen. Die negative P-Bilanz stellt eine ernst zu nehmende Herausforderung für die zukünftige Nahrungsmittelproduktion in der Region dar. Phosphor-Verluste können reduziert werden, wenn Brände in der frühen Trockenzeit vorgenommen werden.

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1 GENERAL INTRODUCTION

All soil nutrient systems are characterized by nutrient loss and gain mechanisms (Table 1.1) that maintain the productivity of the soil. In a given soil nutrient system, characterized by time and geographic location, one or more of the input-output pathways dominates. For instance, besides nutrient losses through the burn of vegetation materials, which do not exist in some natural and agricultural productivity systems, the nutrient loss pathways shown in Table 1.1 take place on all soil nutrient systems. While agricultural fields may be characterized by all the pathways to nutrient inputs (Table 1.1), the inputs through inorganic fertilizer application, manure and compost incorporations do not exist in most natural soil nutrient systems.

Table 1.1 Pathways of nutrient input and nutrient losses that define the total nutrient balance of a given soil nutrient system over a period of time. The sum of nutrient input (+ve) and nutrient loss (-ve) over the defined period is an indicator of a gain in nutrient productivity (+ve) or loss (-ve) in nutrient productivity (degradation)

Nutrient input	Nutrient loss
Wet atmospheric deposition	Errosion (wind, water)
Dry atmospheric deposition	Runoff
Biotic and abiotic atmospheric nitrogen fixation	Leaching
Plant litter fall	Nutrient removal through harvest from fields
Inorganic fertilizer/compost/plant residue application	Removal of plant residues from fields
Manure input	Particulate and non-particulate transfers during burns
	Volatilization losses

In order to understand the temporal productivity of soils of a given region, to compute the total nutrient balance of a system and to assist in decision making on the maintenance of soil productivity, an in-depth understanding of the dominant natural nutrient balancing mechanism of a given region is essential.

Across the northern region of Ghana, annual bush fires result in the transport of plant nutrients from local soils and the concurrent emissions of gaseous products. Knowledge on the fraction of the fire-induced nutrient transport that gets deposited within the region is limited. Such knowledge is essential, as it forms the base for estimating the overall nutrient balance across the region when data on other components of the total nutrient balancing mechanisms (fertilizer application, N_2 fixation, harvesting, erosion, etc.) are available.

1.1 Research aims and objectives

The main aim of this study is to estimate the net partial nutrient balance that exists between annual fire-induced losses on the one hand and the gains due to atmospheric deposition on the other hand. These factors define the temporal productivity of the natural plant nutrient system of soils of the northern region of Ghana. The aim is also to quantify the total annual fire-induced gaseous emissions (CO_2, CO, CH_4, NO_x) across the northern region of Ghana and across entire Ghana to ascertain their impact on the global climate and as an input to the national greenhouse gas inventory. A variety of research tools (e.g., field-based data collection, experiments, chemical analysis, GIS and remote sensing technology, etc.) are used to identify, quantify, analyse, evaluate and predict the impact of the gross fire-induced nutrient losses and atmospheric nutrient deposition on the soils. The research findings specifically enable an estimate of the temporal sustainability or otherwise of soils of the region and identify actions and activities that could be applied to address and minimize negative impacts of fires on soil nutrient depletion.

1.2 Thesis structure

The thesis is organized in six chapters. Chapter 1 introduces the concept of total nutrient balance and the research goals and objectives.

Chapter 2 presents the background for the study and a description of the study area. The occurrence of vegetation fires, wet and dry depositions of plant nutrients across the northern region are evaluated. The underlying conceptual frameworks that form the backbone of the study are given, and the principle underlying sustenance and decline in productivity (degradation) due to temporal nutrient losses are presented. The tools used during the estimation processes are described.

In Chapter 3, the period of occurrence of annual fires, the kinds of vegetation that are burned and the seasonal burned area of each burned vegetation cover type are identified and analyzed through GIS and remote sensing. The land-use conversions between cropland and natural vegetation for the period 2000 to 2008 are analysed and discussed.

Chapter 4 provides the quantification and estimation of the gross fire-induced nutrient losses and gaseous emissions. The losses and emissions are quantified from the field data and then extrapolated across the northern region and entire Ghana. Adequate means to address fire-induced nutrient losses/gaseous emissions are identified and trade-off between the conservation of the nutrients nitrogen (N) and phosphorus (P) with regard to their conservation.

In Chapter 5, the spatial and temporal deposition of wet and dry plant nutrients from July 2010 to June 2011 are quantified as an indicator of the annual return of fire-induced nutrient transports. The two-dimensional (longitude, latitude) distribution of harmattan-dust and rainfall, and the nutrients they deposit are presented. Potential sources of the deposited plant nutrients and sinks to fire-induced nutrient transfers are also discussed. The chapter ends with an estimate of the underlying nutrient balance and a proposed spatial and temporal mechanism of annual nutrient balance between fire-induced losses and atmospheric depositional gains across the northern region of Ghana.

The final chapter of the thesis, Chapter 6, summarizes the main work, findings and conclusions of this study. It also presents some challenges and potential outlooks for further research.

2 BACKGROUND OF STUDY

2.1 Study area

The study covers the northern savanna region of Ghana (Figure 2.1). Geographically located within the Volta River watershed, the region has a total land area of about 70,384 km^2. It constitutes about 29% of the total dry land cover of the country.

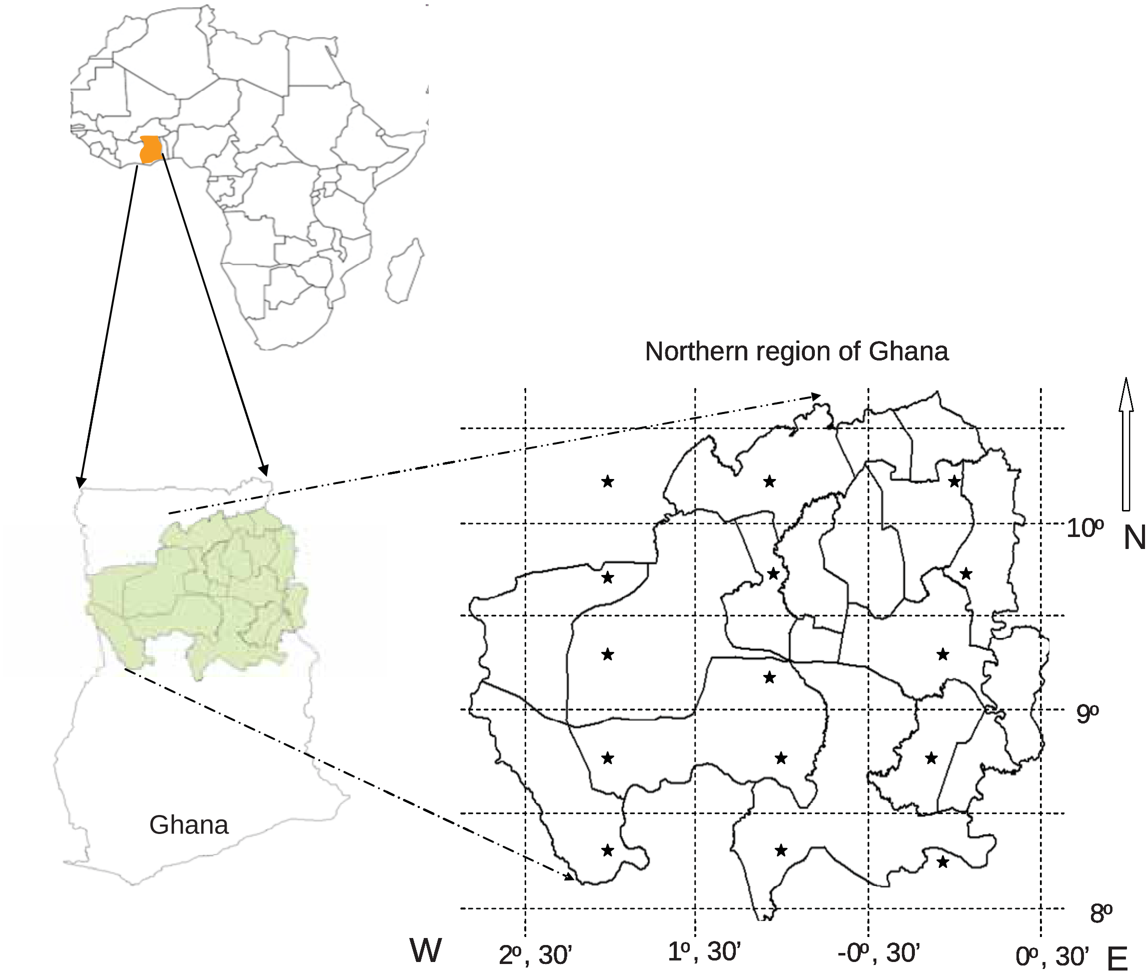

Figure 2.1 Geographic location of the northern region of Ghana showing the imposed division of the region into blocks and the relative locations (★) of sampling sites within each block where wet and dry atmospheric nutrient depositions were collected from June 2010 to July 2011

The region is the largest of the 10 political land regions of the country, and has a population of about 1.8 million people. It comprises of rural areas that generally survive on subsistence-rain-fed agriculture (Braimoh 2004). The high cost of fertilizers, coupled with long distances to fertilizer sales sources mean that most local farmers depend on natural means of nutrient deposition and the adoption of indigenous soil fertility management options such as shifting cultivation and crop rotation for seasonal crop production. As a result, natural means of soil nutrient replenishment are important sources of nutrients for crop production.

2.1.1 Vegetation cover

The vegetation across the study area is mostly savanna (Figure 2.2, FAO 2009) with Guinea savanna characteristics (Dickson and Benneh 1995; Lawson 1985; Taylor 1952).

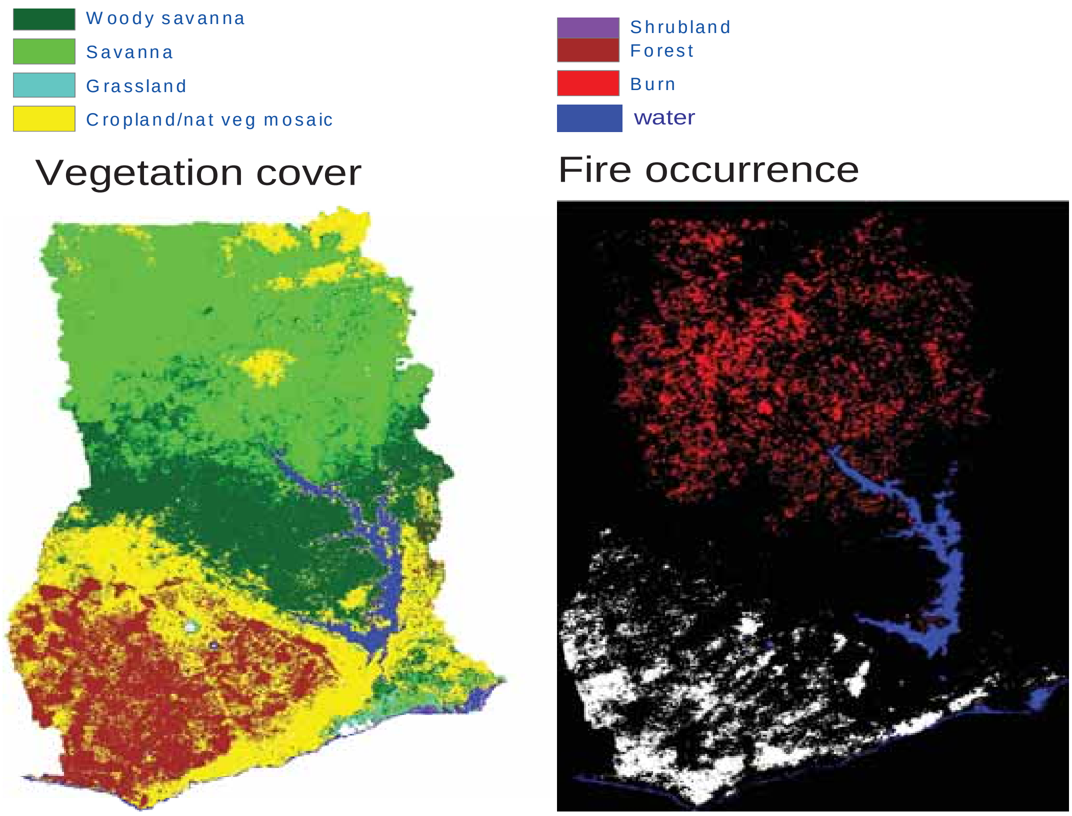

Figure 2.2 Satellite captured vegetation fire occurrence in December 2008 across Ghana and the corresponding vegetation cover that year. Data source: MODIS (Justice et al. 2002).

Savanna vegetation is known to develop due to the influence of anthropogenic factors, rainfall, soil characteristics (Lane 1962) and vegetation burning activities (Archer and Scholes 1997; Sankaran et al. 2004). Bagamsah (2005) categorized the savanna vegetation of the area into four main types according to the relative percentage ground cover of trees: shrubs: herbs as widely open savanna woodland (7:12:8), grass/herb fallow with scattered trees (8:7:65), open savanna woodland (3:64:30), and closed savanna woodland (55:25:5). Common tree species in the study area include those of the families Malvaceae (e.g., *Grewia mollis* Juss), Fabaceae (e.g., *Parkia biglobosa* (Jacq.) R. Br. ex G. Don, and *Tephrosia bracteolata* Guill. & Perr.), and Sapotaceae (e.g., *Vitellaria paradoxa* Gaertner.f.). Shrub species include the family Rubiaceae (*Nauclea latifolia* Sm. and *Diodia scandens* Sw). Herbaceous plant species include the family Icacinaceae (e.g., *Icacina senegalensis* Juss), while major grasses include those of the family Gramineae (e.g., *Andropogon gayanus* Kunth), and the family Poaceae (e.g., *Sporobolus pyramidalis* P. Beauv., *Cymbopogon sp, Pennisetum sp* and *Hyparrhenia rufa* (Nees) Stapf). Combusted fuel loads are mostly leaves, herbaceous plants/grasses and twigs. Combusted twig diameters range from <5 mm to 100 mm. Though broken twigs of diameters >100 mm may burn during fires, burns are not commonly observed on living trees. Agriculture constitutes over 60% of employment. Cultivated food crops include cassava (*Manihot esculenta* Crantz), corn (*Zea mays* Linn.), millet (*Panicum miliaceum* Linn.) and groundnuts (*Arachis hypogaea* L.).

2.1.2 Soils

Soils in the northern region are developed over granite, voltaian shales, sandstones and phyllites (Dickson and Benneh 1995; Tiessen et al. 1991). Lixisols/Luvisols are the major soil groups (FAO 1988). The pH is slightly acidic and ranges between 3.5 and 6.0. The texture of the soil is silty to sandy loam if developed over voltaian shales, or course in texture if developed over granite (Dickson and Benneh 1995).

Although the soils have good drainage during the wet season (Hauffe 1989), hard iron-pan concretions (Owusu-Bennoah et al. 1997) as well as basic intrusions (Wills 1962) are known to underlay most of the soils in the study area. Tiessen et al. (1991) attribute an observed decrease in illite content with depth of soil to aeolian deposits of illites and suggested harmattan-dust deposits as the source of illites. The soils are typically characterized by laterite concrete formations (Owusu-Bennoah et al. 1991; Owusu-Bennoah et al. 2000), and are comparatively lower in organic matter compared to the south-most forest soils. Low moisture characteristics of the soils facilitate plant residue burning and further loss of potential organic matter (Bagamsah 2005).

2.1.3 Climate

The climate is semi-arid and tropical (Wills 1962; Dickson and Benneh 1995) with annual rainfall less than 1200 mm per annum across the northern region (Runge-Metzger and Diehl 1993) and up to 2500 mm per annum across the entire country (Swaine and Becker 1999). Rains occur mostly in the months of May to October. Rainfall across the region is known to be variable and unreliable (Braimoh 2004). The period from November to April is usually dry with little or no rainfall. During this period, dry harmattan-winds reach the country from the northern and eastern directions. The dry conditions facilitate burn of vegetation in the dry season. Mean monthly temperature ranges between 22 °C and 35 °C (Innes 1977).

2.2 Concept of nutrient depletion and land degradation

Soil degradation is a process of decreasing soil quality and results in the loss of soil productivity (Muchena et al. 2005). Land degradation refers to the loss of productivity of the land and its ability to provide quantitative or qualitative goods or services as a result of natural and human-induced changes in physical, chemical and/or biological processes (Blaikie and Brookfield 1987). The degradation of a soil is primarily reflected in a reduction in soil quality and quantity as an input to the production of agricultural crops. Land and soil degradation has been consistently cited as one of the most important threats to the world in terms of food security (Vlek et al. 2010; Scherr 1999; Vlek et al. 2010). Acute land degradation has been reported to have rendered over 320 million hectares of land unsuitable for any meaningful agriculture in Africa alone (Scherr and Yadav 1996; Sant' 2001). Besides land degradation through erosion losses, salinization, loss/inadequate soil biological activities, organic matter loss, acidification, agrochemical pollution, desertification, etc., soil nutrient depletion is a major cause of soil degradation (Oldeman 1994; Hopkins et al. 2001). Soils may also be degraded through the destruction of soil physical properties (reflected in the air and/or soil-moisture-holding capacity of the soil). In areas with little erosion losses, degradation due to soil nutrient depletion constitutes the bulk of annual loss in soil productivity. Knowledge on the quantities and mechanisms of soil nutrient loss across a landscape would aid policy formulation on issues of food security and provide a knowledge base for future decision-support tools for soil health and food production.

Soil nutrient loss takes place in numerous ways (Table 1.1). These include nutrient removal through harvested crops, removal of plant residues from cultivated fields, soil erosion, leaching of plant nutrients to horizons beyond the reach of plant roots, burning and volatilization of plant nutrients (Stoorvogel and Smaling 1990). Depending on the type of agricultural practices observed and the general geophysical conditions of an area such as slope, soil parent material, soil texture, and climate, one or more of the nutrient depletion mechanisms may dominate at any time.

Across the West African savanna landscape, characterized by annual fires, relatively flat lands, and low removal of plant residues from the natural vegetation, vegetation burning is a major cause of plant nutrient loss. Accompanying the annual nutrient losses through vegetation burns are emissions of carbon and greenhouse gases. These emissions have an impact on the environment and the global climate[1]. An estimate of the quantity of NO_x that is annually emitted during fires is important in quantifying the impact of this local pollutant on human health. Knowledge of the amount of the gaseous carbons (CO_2, CO, and CH_4) that are annually emitted through bush fires will also assist in the quantification of the carbon budget of these areas. This helps to predict the contributive impact of annual fire-induced emissions on the global climate change.

Soils get enriched with plant nutrients through various means (Table 1.1), which include mineral fertilizer input, compost/animal manure input, nutrient fixation, and atmospheric nutrient deposition. (Aticho et al. 2011). On the landscape and country level, the holistic mechanisms of nutrient input-output determine the soil nutrient balance of the system. However, one or more of these means of soil nutrient inputs, as well as nutrient loss mechanisms, may dominate at a given time. On cultivated fields, for instance, fertilizer input (Yazdanpanah et al. 2011), compost/manure input (Akbari et al. 2011), and growth of nutrient fixing species (Ahiabor et al. 2007) to enrich the soils comprise the bulk of soil nutrient input. On the other hand, natural vegetation is not intentionally fertilized with organic or inorganic fertilizers.

[1] Climate encompasses the statistics of temperature, humidity, atmospheric pressure, wind, precipitation, atmospheric particle count and other meteorological elemental measurements in a given region over long periods.

The consistent occurrence of annual bush fires and the related nutrient losses (Cook 1994; Dijkstra et al. 2010) over decades should have resulted in a depletion of soil productivity and decline in plant growth in many areas of the world. Across the West African savanna regions where bush fires result in annual soil nutrient losses, there is regrowth of natural vegetation each year. Besides nutrient input through the decomposition of the vegetation's own litter shed (Triadiati et al. 2011), the observed regrowth suggests a natural means of plant nutrient gain across the landscape. With minimum soil nutrient fixation and low fertility of the Guinea savanna soils (Ahiabor et al. 2007), atmospheric nutrient depositions (nutrients deposited by dust particles and nutrients dissolved in rainwater; see section 5.1) are major sources of soil nutrient input across the natural savanna landscape.

Besides nitrogen (N), where the dominant input source may be from biological N_2 fixation, the annual nutrient balance between bush fire nutrient losses and atmospheric depositional gains could serve as an indicator to predict the long-term productive potential of the soils or the potential degradation of soils for future food production. The balance also serves as a knowledge base in formulating informed policies that aim to sustain the environment and the agricultural productive potentials of the soils. Across these fire-prone West African savanna regions, such knowledge is limiting.

2.2.1 Bush fire occurrence across the savanna region of Ghana

Vegetation burning in the Sahelian region of Africa is a common practice (Barbosa et al. 1999a; Cahoon et al. 1992). From the very first satellite fire images obtained from the Advanced Very High Resolution Radiometer (AVHRR) (Stroppiana et al. 2000), the savanna areas of Africa were identified as the region with the highest occurrence of vegetation fires around the globe (Dwyer et al. 1999; Dwyer et al. 2000). In Ghana (Figure 2.1, Figure 2.2), though no exact period of occurrence has been reported in the literature, bush burning is generally known to take place during the dry season (November to March). Large areas of natural vegetation are annually burned in the process.

The fires have both natural and anthropogenic causes (Sheuyange et al. 2005; Bowman et al. 2011). They are affected by environmental, seasonal climate, and geophysical conditions such as fuel load, fuel moisture, relative humidity, wind speed and ambient temperature. Ignition by lightning is the main natural cause of bush fires. Anthropogenic activities such as seasonal land clearing for farming and hunting (Sheuyange 2002) are reported to be the main cause of bush burning across West African. Farmers burn vegetation covers during land preparation, for weed control, to rid the land of crop debris, and to remove rubbish. Arsonists may set vegetation on fire indiscriminately, while cigarettes discarded irresponsibly initiate fires across the region. Van Wilgen et al. (1990) reported that the anthropogenic source of vegetation fire accounts for over 70% of all fires across the African continent. The greater the fuel load (with adequate spacing), the more intense the fire (Wade 2011; Engber et al. 2011). Compact logs consequently burn longer than twigs whereas dry grasses burn comparatively rapidly. High ambient temperatures bring fuel loads closer to their ignition point thereby easing the burn initiation and spread. Winds continuously supply oxygen and help the spread of fires to neighboring vegetations. The stronger the wind therefore, the greater the spread of bush fires (White et al. 2011). On the other hand, burns are impeded by the moisture content of vegetation at the time of burn (Kreye et al. 2011) and by the relative humidity of the surrounding air. For a given fuel load, the higher the fuel moisture content/relative humidity, the slower the burn. Burns across the West African savanna region are enhanced by drying up of vegetation by dust-laden, dry-seasonal north-easterly surface winds (Harmattan) that render vegetation vulnerable to burn in the dry season. The regularity of annual bush fire occurrences (Diaz-Delcado et al. 2003) may have contributed to the establishment of the savanna landscape across the region (Archer and Scholes 1997; Sankaran et al. 2004; Thonicke et al. 2001).

2.2.2 Environmental and agricultural impact of annual bush fires on savanna landscapes

Bush fires are part of the natural ecosystems of most savanna landscapes (Saamak 2001). They are the main buffering element that maintain the structure of the savanna system and prevent formation of forests (Getzin 2002; Jeltsch et al. 2000) by keeping a balance between tree species and grasses (Scholes and Walker 2004; Higgins et al. 2000). Fire impacts ecological succession. It discourages diseases and insects, affects ecosystem sustainability and prevents flowering and/or seeding of some tree species

(Wuver et al. 2003; Dayamba 2010). Some plants require heat or products of fire to grow. For instance, the whispering bells (*Emmenanthe penduliflora* Benth. Var. rosea*)* sprouts when exposed to the NO_2 in smoke (Mlot 1997).

Ecosystems that depend on fire may thus become unstable without it. Plant nutrients such as N and P may be taken up and stored in plant tissues and may not be available for cyclic plant growth. This has a negative influence on, for example, seedling establishment, or may result in stresses at a later stage. Wildlife numbers and diversity could decline as a result of the decline in plant growth. Annual bush fires therefore play a major role in determining the shape, structure and function of most savanna ecosystems and lead to the formation of existing communities (Parr and Brockett 1999). Besides herbivory, fire is the most important determinant of the inherent structure imposed on savanna ecosystems by climate and soil. Fire may cause simultaneous germination of some species such as the kapok (*Ceiba pentandra* (L.) Gaertn.) and *Terminalia avicennioides* Guill. & Perr. (Duval 2008; Dayamba 2010). Burns may affect germination of some plant seeds. Heat from bush fires breaks dormancy in some thick-coated seeds while it destroys the viability of other seeds (Wuver et al. 2003), eventually determining the vegetation composition of the savanna ecosystem. Fires may lead to a changed soil-microbial composition (Andersson et al. 2004). The extent of bush fires and the patches of unburned vegetation created are critical to the survival and hence the population of most plant and animal species.

Pollution caused by smoke, particulate matter and gaseous emissions is detrimental to human health (Langmann et al. 2009). During annual vegetation burns, large amounts of carbon dioxide (CO_2) and other greenhouse gases are emitted into the atmosphere. These greenhouse gases absorb and re-emit radiation (within the thermal infra-red region) from the earth's surface, a process that results in the warming up of the earth's atmosphere thereby affecting the global climate (Crutzen and Andreae 1990; Lehsten et al. 2009). Each greenhouse gas has a different warming potential. For instance, a unit mass of N_2O has 310 times the global warming potential (GWP) of a unit mass of CO_2, while CH_4 has about 21 times for a time horizon of 100 years (Boucher et al. 2009). The higher the quantity of atmospheric greenhouse gases, the stronger the warming of the global climate. Since vegetation removes CO_2 from the atmosphere during the process of photosynthesis, plant destruction during annual fires also results in the removal of the natural sinks for CO_2 capture from the atmosphere and subsequent assimilation into plant tissues. The consistent annual bush-fire carbon-sink removal through burns and the related direct carbon and greenhouse gas emissions into the atmosphere therefore contribute to the observed changes in the global climate.

Agricultural losses due to bush fires are divers (Andersson et al. 2004; Cook 1992). Fire results in abrupt physical destruction of vegetation and it's related ecosystem function (Arseneault et al. 2007; Lecomte et al. 2006). They result in direct loss of plant and animal life. Fire destroys the soil aggregate structure and water-holding capacity (Ravi et al. 2010). It results in the combustion and volatilization of volatile soil- and plant-constituent elements (Bagamsah 2005; Caldwell et al. 2002; Keene et al. 2006). Bush burning therefore results in the direct losses of essential plant nutrients (N, P, K, Ca, Mg) (Andersson et al. 2004; Cook 1992; Debano and Conrad 1978; Wells et al. 1979), and functional plant nutrients (e.g., Na) (Subbarao et al. 2003). In the northern region of Ghana, bush fire has been suggested to be a reason for the observed decline in soil fertility (Abatania and Albert 1993; Gordon and Amatekpor 1999; Agyemang 2011). Nutrient-rich ash that remains after vegetation burning may be transported from the burned sites to other areas through surface erosion losses (Wells et al. 1979), it may be leached to lower horizons beyond plant root zones (Stark 1977), or may be carried along by runoff (Núñez-Delgado et al. 2011; Debano and Conrad 1978) and wind to different sites, resulting in a local loss of plant nutrients (Binkley and Christensen 1991). Temporal loss of plant nutrient manifests in reduced plant growth, degraded soils and environment, and an unsecured future food production. The demerits of annual fires far outweigh their merits (Paul et al. 2010).

Across the savanna areas of West Africa, only few studies exist relating plant nutrient losses due to bush fires to their consequences for soil degradation and the foreseeable impact on food security. The available studies often omit some aspects of the loss quantification parameters and are not complete. For example, dry-season bush burning across the northern region of Ghana is observed between November and March of each year. Bagamsah (2005) estimated net annual bush fire losses for N, P and K in the northern region of Ghana to be about 10-22 kg N ha $^{-1}$, 1-7 kg P ha $^{-1}$ and 2-12 kg K ha $^{-1}$, based only on a 2-month estimation (December and February). Annual nutrient loss based on two months of data serves as a proxy for predicting the annual nutrient losses. However, data on nutrient losses during burns in November and January could add to the existing data and give a clearer picture on the seasonal variations in fire-induced elemental losses. Bush fire nutrient losses need be quantified for the entire period when the fires occur in order to project the potential for depleting the soil nutrient resource against the background of the expected increase in food demand for the ever increasing human population.

The temporal cumulative effect of annual vegetation-burns and the related plant nutrient losses should have detrimental effects on current and future soil productivity parameters across the region. This is not, however, observed in the short term, suggesting some form of nutrient balancing mechanism through nutrient gains is operating.

2.2.3 Environmental and agricultural impact of annual nutrient deposition

Atmospheric nutrient deposition is an essential source of soil nutrient replenishment (Baker et al. 2007; Baker et al. 2006; Ellis et al. 1983; Soderberg and Compton 2007) after a loss such as through vegetation burning (Stoorvogel et al. 1997). Though N losses are mostly replaced through atmospheric N_2-fixation processes, the exact quantitative estimates across different vegetation types are not exactly known. In areas with limited nitrogen-fixing species, limited cultivated lands and limited fertilizer/organic matter input, absence of irrigation, absence of groundwater inputs, etc., the main source of soil nutrient replenishment is atmospheric deposition, i.e., either wet deposition through solvation of gaseous species such as NH_3 and NO_x by precipitation (Hu et al. 2003) and/or dry deposition from aerosols, dust particles and gases (Baker et al. 2007; Walker et al. 2004). Across Ghana, dust deposition during the harmattan season is reported to be an essential source of plant nutrients (Stoorvogel et al. 1997). High soil macro-nutrient concentrations have been variously reported in Saharan dust and aerosols for N (Baker et al. 2003; Baker et al. 2007), P (Baker et al. 2007; Herut et al. 2002), and K, Ca, Mg and Na (Stoorvogel et al. 1997; Tiessen et al. 1991).

Some attempts have been made over the past years to quantify the plant nutrient content of rainfall and harmattan-dust particles across Ghana (Tiessen et al. 1991; Akoto et al. 2011; Breuning-Madsen et al. 2012). These studies often concentrate on a unit location or on the rainfall/dust nutrient variability in a single direction. Tiessen et al. (1991) quantified the deposition of K, Mg, Ca and Na by harmattan-dust but only at a single location (Nyamkpala) in the northern region of Ghana. Similarly, Breuning-Madsen et al. (2012) estimated the nutrient input of harmattan-dust in a longitudinal direction around the Volta Lake of Ghana, while Breuning-Madsen and Awadzi (2005) quantified the dry harmattan sediment depositions in a longitudinal direction across the country. Mean estimates from these field-measured values may invariably fail to be representative of the entire region. Besides, knowledge about the spatial and temporal distribution of rainfall/harmattan-dust and the nutrients they deposit across the country is limited. Filling this knowledge gap is essential in estimating the nutrient balance as an indicator for monitoring the sustenance of the soil's productivity.

2.2.4 Nutrient balance as a mechanism for sustenance of soil productivity

Compensatory mechanisms may exist between annual bush fire nutrient losses on the one hand and annual nutrient gains through atmospheric deposition on the other. For the fragile soils of Sub-Saharan Africa, which are reported to be easily degraded and deteriorating at an alarming rate (Vlek 1993; Vlek et al. 2010), comprehensive and in-depth studies on annual nutrient depositional dynamics after bush burning are important for understanding the overall natural nutrient cycling mechanisms. This is essential in estimating the temporal fate of soil nutrients and in understanding the dynamics involved in soil nutrient cycling, a process that might have kept the unproductive soils of the savanna landscape sustainably productive after consistent annual bush-fire losses.

2.3 GIS remote sensing for mapping of burned vegetation covers

Satellite imagery analyses have been used to complement data collection (ecological) from broad spatial extents and access (ecological) data that are difficult to collect by contemporary field-based methods (Kerr and Ostrovsky 2003; Lu and Weng 2007). Remote sensing has been used as an effective technique to map vegetation cover type distribution (Tucker and Sellers 1986; Friedl et al. 2010; Latifovic et al. 2004) and to analyze and map areas that are seasonally burned (Giglio et al. 2003; Barbosa et al. 1999b; De La Riva et al. 2004; Devineau et al. 2010; Justice et al. 2002; Roy et al. 2002). Examples of satellite-analyzed vegetation cover and daily burned area maps (see section 3.1.2) are the Land Cover Type Yearly L3 Global 500 m product (MCD12Q1) and the Burned Area Monthly L3 Global 500 m (MCD45A1) (Roy et al. 2002; Roy et al. 2005; Roy et al. 2008), respectively, both obtained from analyses of earth surface reflectance by the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites. Such twin analyses coupled with field-based nutrient estimates provide the base to quantify total annual nutrient losses, carbon and greenhouse gas emissions during bush fires across a given region.

2.4 Conceptual framework

Net plant nutrient balance in this study is considered to be the difference between direct nutrient loss through vegetation burning and direct nutrient input through atmospheric nutrient deposition (Figure 2.3). Secondary nutrient losses that may indirectly occur after burning (Caldwell et al. 2002; Keene et al. 2006), such as leaching of plant nutrients (Stark 1977; Paul et al. 2010) and erosion losses (Wells et al. 1979; Ravi et al. 2010) are not considered in this study. Quantification of annual bush fire plant nutrient losses and annual depositional gains in this study involve determination of aboveground plant nutrient load distribution in the region before and after controlled vegetation burning experiments, and use of GIS and remote sensing techniques to map vegetation cover type distribution from which seasonal and annual losses are estimated using time series monthly burned area products. Dry and wet vertical and horizontal spatio-temporal depositional gains are directly measured on-field across the study area.

2.4.1 Direct nutrient loss through vegetation-burning

Nutrients are directly lost through vegetation burning in the form of particulate matter (Cook 1992), and through volatilization of gaseous species (Cook 1994; Keene et al. 2006; Shombe 2011). GIS and remote sensing techniques of earth observation systems have been used to map annual areas of daily fire activities across the globe (Giglio et al. 2003; Justice et al. 2002). Maps of burned areas can serve as important tools in estimating annual temporal land coverage that is seasonally burned. From the obtained data, the associated plant nutrient losses can be estimated after ground truthing.

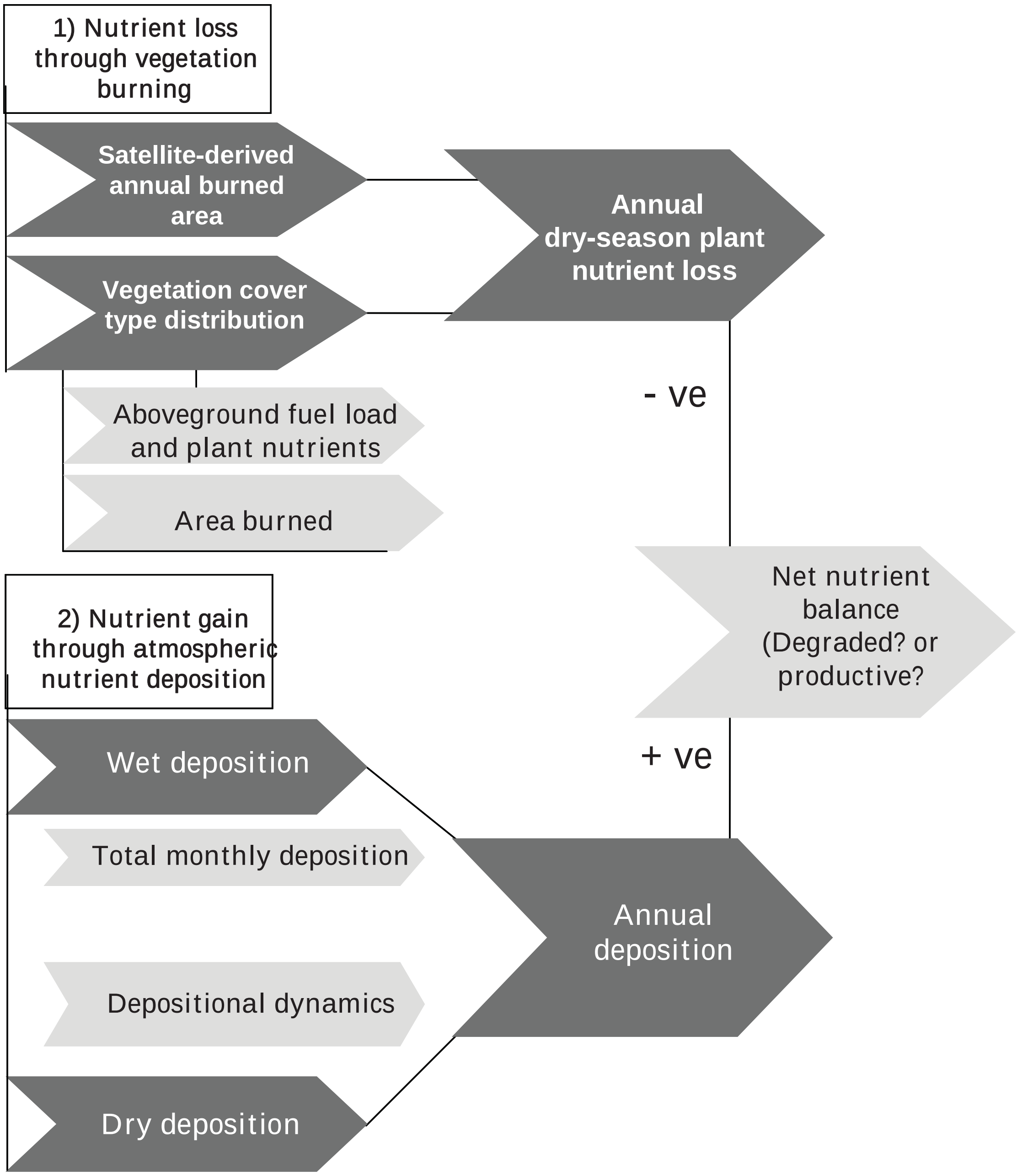

Figure 2.3 Conceptual framework for the analysis of net nutrient balance between direct vegetation-burn losses and atmospheric depositional gains across the northern region of Ghana. –ve is nutrient loss, +ve is nutrient deposition

Vegetation cover type distribution maps can be obtained by vegetation cover classification using GIS and remote sensing techniques (Bartholomé and Belward 2005; Friedl et al. 2010; Price 2003). Once the vegetation cover type distribution categories in an extended area are known, plant nutrient losses due to bush burning can be estimated for each vegetation cover type by overlaying the vegetation cover type category map with the burned area map and statistically identifying the area extent of each category burned in each period (e.g., month) of the year. This procedure can be repeated for each month and for the past years depending on the availability of the remote sensing data to estimate the mean average monthly/annual burned areas of each vegetation cover type.

Because the quantity of combustible plant fuel load varies with time, on-field burning experiments are then conducted to monitor the seasonal losses of plant nutrients during bush burning for each of the categorized vegetation cover types. The difference between plant nutrient load of the vegetation before combustion and that of the ash is an estimate of direct nutrient loss due to burning for the given vegetation type in a given month. Carbon emission/plant nutrient losses across the entire study area can then be estimated by overlaying the burned area map and the land-cover category map and statistically computing the total of each vegetation type that was burned. Belowground combustible plant materials are usually not burned during the bush fires in the study area, hence are not considered in this study.

The sum of average nutrient losses and emissions by each vegetation type is the estimate of direct total plant nutrient loss and direct emissions to the atmosphere as a result of vegetation burning across the study area.

2.4.2 Direct nutrient gain through atmospheric deposition

Annual nutrient depositions in this study are considered to be of two kinds: Wet deposition, which is solely due to nutrient input through precipitation (Hu et al. 2003), and dry deposition through settling dust (Stoorvogel et al. 1997; Tiessen et al. 1991) and aerosol particles (Figure 2.3).

Wet deposition forms part of the total nutrient replenishment of a region. Plant nutrients that are lost to the atmosphere during vegetation combustion or from other sources may return to the soil through solvation of gaseous species such as NH_3 in rainfall. These dissolved nutrients become available to plants. Across the northern region of Ghana, annual rains with the associated wet nutrient deposition form part of the natural plant nutrient cycle.

In the dry season (November-February), north-easterly trade winds accompanied by dust (harmattan), blow from the Sahel region into the country (Tiessen et al. 1991). The harmattan-dust is reported to contain essential plant nutrients

(Stoorvogel et al. 1997; Tiessen et al. 1991) and is believed to be part of the soil nutrient replenishment mechanisms across the region. It is, however, difficult to distinguish between the nutrients brought into the region by harmattan-dust and the nutrients redistributed from local soils by wind erosion. Collection of dust at greater heights above the ground may, however, correct for harmattan-dust, reducing the error term in the local redistribution of inherent soil nutrients. The sum of annual wet and dry nutrient deposits gives the bulk atmospheric nutrient deposit across the study area.

In order to understand the dynamics involved in annual atmospheric nutrient deposition, determination of spatial nutrient distribution across the entire study area is necessary. It is anticipated that most of the nutrients lost during burning may vertically fall back to the soil in a relatively short time if not transported horizontally by atmospheric wind to another point. Annual nutrient gain due to deposition covers a given area. It is not a point deposition that occurs only at sites of vegetation burning, and may vary from one point to another within a given area. Spatio-temporal nutrient depositional dynamics across the entire study area will therefore aid understanding of the distribution of nutrient deposits across the region.

2.4.3 Net nutrient balance between burning losses and depositional gains

The difference between estimated direct nutrient loss through vegetation burns (section 2.3.1) and the quantified direct nutrient gain through atmospheric deposition (section 2.3.2) is the net nutrient balance between annual burning losses and annual deposition gains across the region. This variable predicts the natural sustainability or otherwise of soils of the region. Together with the annual carbon/greenhouse gas emissions across the region, the net nutrient balances serve as a decision-support tool for relevant institutions and policy makers for monitoring soil productivity, future food security and global climate change.

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3 SPATIO-TEMPORAL BUSH FIRE OCCURENCE ACROSS GHANA

3.1 Introduction

3.1.1 Background

Earth orbiting platforms are equipped with sensors to take spatio-temporal images and photographs of the earth in periodic time intervals. Information extracted from such images is used to predict the occurrences of natural phenomena over the earth's surface. The mechanisms of satellite imagery and surface reflectance inferences are provided in detail by Campbell (1996), Curran (1985), and Lillesand and Kiefer (1993). Basically, differences in reflected solar radiation by different surfaces define the nature of the reflecting surface based on similarities in reflecting properties to those of other known materials.

Satellite images come in different spatial and temporal resolutions. The satellite QuickBird-2, for instance, is mounted with two sensors that record surface reflectance at different wavelength ranges. The multi-spectral sensor has a pixel resolution of 2.44-2.88 m, while the panchromatic sensor has a finer resolution of 61-72 cm. The spatial resolution of Landsat images ranges from 15 m to 120 m, while varying spatial resolutions are captured by other onboard satellite sensors such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, 15 m, 30 m and 90 m), the multi-spectral and panchromatic sensors on the Ikonos-2 satellite and the Orbview-3 satellite (4 m and 1 m), and the MODIS sensor onboard the Terra and Aqua satellites with spatial resolutions of 250 m, 500 m and 1 km (Melesse et al. 2007). Variations in spatial and temporal resolution allow temporal capture of earth surface phenomena at varying degrees of details.

Satellite imagery has been effectively applied in climate and meteorological studies (Seiz et al. 2011), geology, forestry, agriculture and many other fields (Melesse et al. 2007). It has been used in hydrological modeling (Finger et al. 2011), in energy and water flux estimations, and in mapping watershed properties (Mohamed et al. 2011). These applications have greatly improved the monitoring of natural phenomena, their assessment and prediction of natural events in various fields. In agriculture, forestry and environmental sciences, satellite imagery has been used in land-use planning, land-cover assessments, and in monitoring of land-use and land-cover changes.

3.1.2 Satellite imagery for estimation of vegetation cover and burned areas

The structure and function of leaves to a large extent depend on the organelle chloroplast, stomata characteristics and evapotranspiration. These properties in turn determine the transmission, absorption and reflection of incident solar radiation from plants. Differences in leaf surface reflectance properties are thus used to determine vegetation cover in satellite imagery (Tucker and Sellers 1986). Based on this mechanism, a number of spatial and temporal land-cover products have been developed (Friedl et al. 2010; Zhan et al. 2006; Ganguly et al. 2010). Ganguly et al. (2010) describe the MODIS product Global Land Cover Dynamics, which provides spatial and temporal changes in phenology across the globe at a fine resolution of 500 m. Friedl et al. (2010) describe a refined algorithm for the georeferenced MODIS collection 5 global land cover (MCD12Q1) (Friedl et al. 2002), which is produced in an 8-day interval on 16 days of MODIS surface reflectance data, and at a spatial resolution of 500 m. The MCD12Q1 algorithm aggregates 8-day pixel values to 32-day averages and on a 12-set calendar year base.

MCD12Q1 consists of 5 different vegetation classification systems: Plant function type classification (PFT), biome classification, University of Maryland classification, MODIS LAI/FPAR classification, and the International Geosphere-Biosphere Programme classification (IGBP, Loveland and Belward 1997). The IGBP classification identifies 17 land-cover classes made up of 11 natural vegetation classes, 3 developed and mosaicked land classes, and 3 non-vegetated land classes. Cross validation analyses indicate that IGBP classification of MCD12Q1 has an overall accuracy of 74.8% with a 95% confidence interval of 72.3%-77.4%. High classification errors are reported between classes that encompass ecological and biophysical gradients and those that are functionally similar in spectro-temporal properties. With these characteristics, MCD12Q1 adequately classifies vegetation cover at a given time and geographic location.

For a given vegetation type (same fuel load), the gross nutrient loss/transfer due to bush burning is directly proportional to the area of vegetation burned. Gaseous emissions due to vegetation burning are also directly related to the area of vegetation burned through the equation:

$$E = A \cdot FL \cdot C \cdot EF \qquad (2.1)$$

where E is the amount of product emitted (g), A is the area of vegetation-burned (m^2), FL is the fuel load before burn (g), C is the combustion factor indicated by the completeness of combustion (%), EF is the emission factor (g gaseous emission kg^{-1} of combusted fuel load) characterized by the amount of the specific gaseous species produced during the combustion (Korontzi et al. 2003). Knowledge on the land area of different vegetation types that are seasonally burned is therefore a base for quantification of fire-induced nutrient losses and emissions.

The MODIS burned area product MCD45A1 (Chuvieco et al. 2008; Roy et al. 2002; Roy et al. 2005; Roy et al. 2008) is a MODIS product (collection 5) achieved by recently adopted algorithms that spatially map the extent of burned areas on a daily basis. MCD45A1 has both MODIS Aqua and MODIS Terra data as input sources with a spatial resolution of 500 m. The accuracy statistics of MCD45A1 show that it correctly classifies 91-99% of total pixels and has a commission error of 0.0842 to 0.6549 and an omission error of 0.2955 to 0.9145 across southern Africa. In general, MCD45A1 captures between 73% (Tsela et al. 2010) and 75% (Roy and Boschetti 2009) of true burned area mapped by the 30-m resolution Landsat enhanced thematic mapper plus.

MCD12Q1 and MCD45A1 provide adequate geographic assessments of fire occurrence and impact of annual fires on agricultural productivity and the environment.

3.1.3 Problem statement

There is limited documentation on the period, extent, frequency and proportions of different vegetation categories that are annually burned across Ghana and in particular, the northern savanna region of Ghana where annual bush burning is observed. Reports on the annual period of bush burns often depend on guesses by indigenous people. In this regard, burns that occur in the larger uninhabited interior vegetation may not be covered; hence reports may be biased towards burns that take place around human settlements. This restricts any effort to quantify gross annual plant nutrient transfers, net nutrient losses and total annual carbon equivalent emissions that are due to vegetation burning across the region.

3.1.4 Aims and objectives

The aims in this part of the study are to:

1. Identify the vegetation cover across entire Ghana and the northern region of Ghana
2. Identify the period of annual fire occurrence across the northern region of Ghana
3. Analyze annual and seasonal burned area extent per vegetation cover across the northern region of Ghana and across Ghana over a 10-year period (2001-2010).

3.2 Materials and methods

3.2.1 Image processing and image analyses

MCD45A1 was used to identify burned areas in the study while MCD12Q1 was used as a land-cover map to identify vegetation cover prior to burning. The 500-m resolution satellite image was used because it provides both a vegetation cover map and a burn area map for the same location and time, which is not the case with higher precision images that mostly produce only one of the two required images. Besides, these images were available for all the years considered in the study (2001-2010) which is also not the case with the relatively young high-precision images. Actual burn areas were extrapolated from the coarse resolution MODIS burned area data, and the 25% error of underestimation reported by Roy and Boschetti (2009) in order to reduce uncertainties associated with burn areas between 30-m^2 and 500-m^2 resolution.

Ten years of data (2001 to 2010) were used in the analyses. Four tiles per month of burned area and land-cover images that fall beyond the perimeter of Ghana were downloaded from ftp://e4ftl01.cr.usgs.gov/MOTA/MCD45A1.005/ (last accessed on 29.01.2012) and ftp://e4ftl01.cr.usgs.gov/MOTA/MCD12Q1.005/ (last accessed on 01.02.2012), respectively. The images were digitally processed using the ERDAS Imagine image processing software (Version 8.6). The 4 tiles were imported into ERDAS Imagine and mosaicked into a single image. Images were geometrically corrected and resampled by the nearest neighbor algorithm.

For the cover types that in the study area (Table 3.1), annual fires only take place on some, e.g., savanna, grassland, shrubland. A 25% error of burn area under estimation was used to reduce the uncertainty associated with the burned area resolution (section 3.1.2). Land-cover images were analyzed and recoded into the 7 most frequently occurring natural land-cover types across the study area (Table 3.1). Open shrubland vegetation and closed shrubland vegetation were merged into a single vegetation type (shrubland vegetation), because they have similar combustible undercover characteristics and comparatively low combined percentage area of coverage (0.21 and 0.05%, respectively; see table 3.1). Together they cover only 0.1% of the total land area burned, hence with relatively minimal error. Burn images were recoded into the land-cover types burned vegetation (represented by the Julian day of fire occurrence), unburned vegetation and unburnable/undetectable fire (water, aerosol and pixels without enough data).

A 3 (burned condition) by 7 (land-cover type before burn) GIS (geographic information system) matrix was then computed to identify land-cover types that were burned and unburned. This process was repeated for each vegetation cover in each month of the year after which monthly and annual burned area averages were computed.

A similar GIS matrix was used to compute annual land-use change involving croplands converted into natural vegetation (CCNV) and natural vegetation converted annually into cropland (NVCC) from 2001 to 2008. In this analysis, 50% crop coverage is used for pixels identified as cropland/natural vegetation mosaic. The relative distribution of cropland compared to natural vegetation in a cropland/natural vegetation mosaic varies from one geographic location to another. An error of 40% was assigned to this relative distribution based on field observations between June 2010 and July 2011. The difference between NVCC and CCNV is the net annual conversion (NAC). The sum of the NAC over the 8-year period gives the net land-use conversion over the period. The proportion of mean average NAC that is due to vegetation burning show burns that are not balanced by natural regrowth of vegetation and which may result in net emission of CO_2 into the environment.

3.2.2 Limitations and uncertainties associated with the area of vegetation burn

Only values reported as true burn areas by the MODIS platform were used in this study. Extrapolating the true area of vegetation burns to the 25% underestimation (Roy and Boschetti 2009) captures burned areas up to 30-500-m resolution. Uncertainties associated with burns below 30-m resolution are not captured. This uncertainty results in underestimation of the actual burned area. Nonetheless, most of this uncertainty is cancelled out by uncertainties due to overestimation of smaller fires that are captured by the platform (Tsela et al. 2010; Roy and Boschetti 2009).

Pixels without enough data are also excluded from the burned area analyses because the area constituted below 0.001% of the land area of the northern region during November, December, and January burns, and below 0.3% during February burns.

For such coarse resolution, it is equally likely that vegetation types are incorrectly identified and mixed up in some cases. In such a situation, the true vegetation cover does not have the unique characteristics (e.g., grassland, shrubland) of the category that it is assigned to but a mixture of two or more different vegetation categories. No treatment could be given to this uncertainty. Cover type was used as identified by the MODIS platform.

3.3 Results and discussion

3.3.1 Land cover of Ghana and the northern region of Ghana

Savanna is the most common dry land cover and the most abundant vegetation cover of the study area (Table 3.1). It covers about 38% and 84% of Ghana and the northern region of Ghana, respectively. Savanna vegetation is believed to develop due to the influence of anthropogenic factors, rainfall and soil characteristics (Archer and Scholes 1997; Sankaran et al. 2004). Given the temporal consistency of burns across the study area, annual vegetation burns may contribute to the establishment of savanna vegetation across this area. Young trees may not get established or mature into old trees due to stress of previous burns.

Vegetation cover across the northern region of Ghana follows the order savanna>woody savanna>grassland savanna>shrubland savanna>deciduous broadleaf forest. The observed IGBP vegetation distribution agrees with field studies conducted across the region by Bagamsah (2005), who categorized the vegetation in the region into five main types in the order grass/shrub savanna (IGBP = savanna) >grass/tree savanna (IGBP woody savanna) >grass savanna (IGBP = grassland savanna)>shrub savanna (IGBP = shrubland savanna)>tree savanna (IGBP = deciduous broadleaf forest).

Table 3.1 Annual dry land cover (10 km^2) of Ghana and the northern region of Ghana from 2001 - 2009 showing the dominant vegetation cover across the region

Dry land cover	Mean	SEM	95% confidence interval of mean		Mean % cover
			Lower	Upper	
Northern region of Ghana					
Savanna	5915	124	5620	6209	83.56
Woody savanna	663	108	408	918	9.36
CNVM*	413	20	365	460	5.83
Grassland	26	8	7.2	45.4	0.37
Cropland	24	4	14.7	34	0.34
Closed shrubland	15	4	4.4	24.7	0.21
Deciduous broadleaf forest	6	1.5	2.9	10	0.09
Urban and built up	4.8	0	4.8	4.8	0.07
Permanent wetland	4.4	1.4	1	7.8	0.06
Barren or sparsely vegetated	4.3	1.8	0.1	8.5	0.06
Open shrubland	3.8	1.5	0.2	7.4	0.05
Ghana					
Savanna	8942	220	8422	9461	37.76
CNVM*	6254	287	5575	6933	26.41
Woody savanna	3986	224	3458	4515	16.84
Evergreen broadleaf forest	3065	197	2600	3530	12.94
Cropland	618	17	578	657	2.61
Grassland	260	16	223	297	1.1
Permanent wetland	180	17	141	221	0.76
Urban and built up	123	0.1	123	123	0.52
Closed shrubland	107	18	63.7	151	0.45
Barren or sparsely vegetated	46	19	2.5	90	0.2
Deciduous broadleaf forest	46	7.2	28.4	62.5	0.19
Open shrubland	39	11	13	65.6	0.17
Mixed forest	5.2	2	0.6	9.8	0.02
Deciduous needleleaf forest	3.6	0.9	1.6	5.7	0.01
Evergreen needleleaf forest	1.3	0.3	0.5	2	0.02

N = 9, SEM = Standard error of mean, Lower = lower bound, Upper = Upper bound, CNVM: Cropland /natural vegetation mosaic*

Compared to the other parts of Ghana, the northern region experiences more burns (Figure 2.2). Savanna vegetation and grassland vegetation have higher herbaceous strata than the more woody vegetation further south, which explains the observed higher fire occurrence across the northern region.

In contrast, the relatively higher percentage cover of woody savanna (≈17%) and other tree vegetation types across Ghana than in the northern region (≈9%) reflects the influence of annual burns on the establishment of matured tree species (Archer and Scholes 1997) and the subsequent establishment of savanna vegetation with a few scattered trees, shrubs and herbaceous species across the northern region of Ghana.

3.3.2 Annual daily fire occurrence across the northern region of Ghana

A constant periodic annual trend and similar seasonal trends were observed in the daily burned area from 2001 to 2010 (Figure 3.1a). Figure 3.1b shows the 10- years mean average daily fire occurrence across the northern region of Ghana for the months of the dry season. Burns start the first week of November and end around the first week of March.

The area of land burned daily increases during this period and reaches a maximum towards the end of the year after which there is a daily decline. Between Julian day 65 (March) to about 300 (October), there is virtually no burn across the region. The observed time sequence of burning is related to the period of the rainy season and the harmattan dry seasons. Rainfall across the study area is common from May to October of each year. Plants therefore accumulate combustible biomass in this period, though this is less so if it has been affected by a burn in the previous dry season. High plant moisture content during the rainy season impedes vegetation burn (Towne and Kemp 2008). In November, when the harmattan dry season sets in, and towards the end of the year (mid dry season), the accumulated combustible plant biomass dries up and becomes vulnerable to burn. Around villages and human settlements, farmers undertake controlled early burns by cutting down grass and burning it. This results in a fragmented grass cover that can be progressively burned without risk to village properties and inhabitants. Also, farmers and herd-keepers generally prefer early burning that allows more regrowth of grass for cattle. Since fire is used in hunting and in land preparation for agriculture, cyclic annual burn has evolved to be closely associated with the cultural and socio-economic activities of the local people, supporting more economic livelihoods.

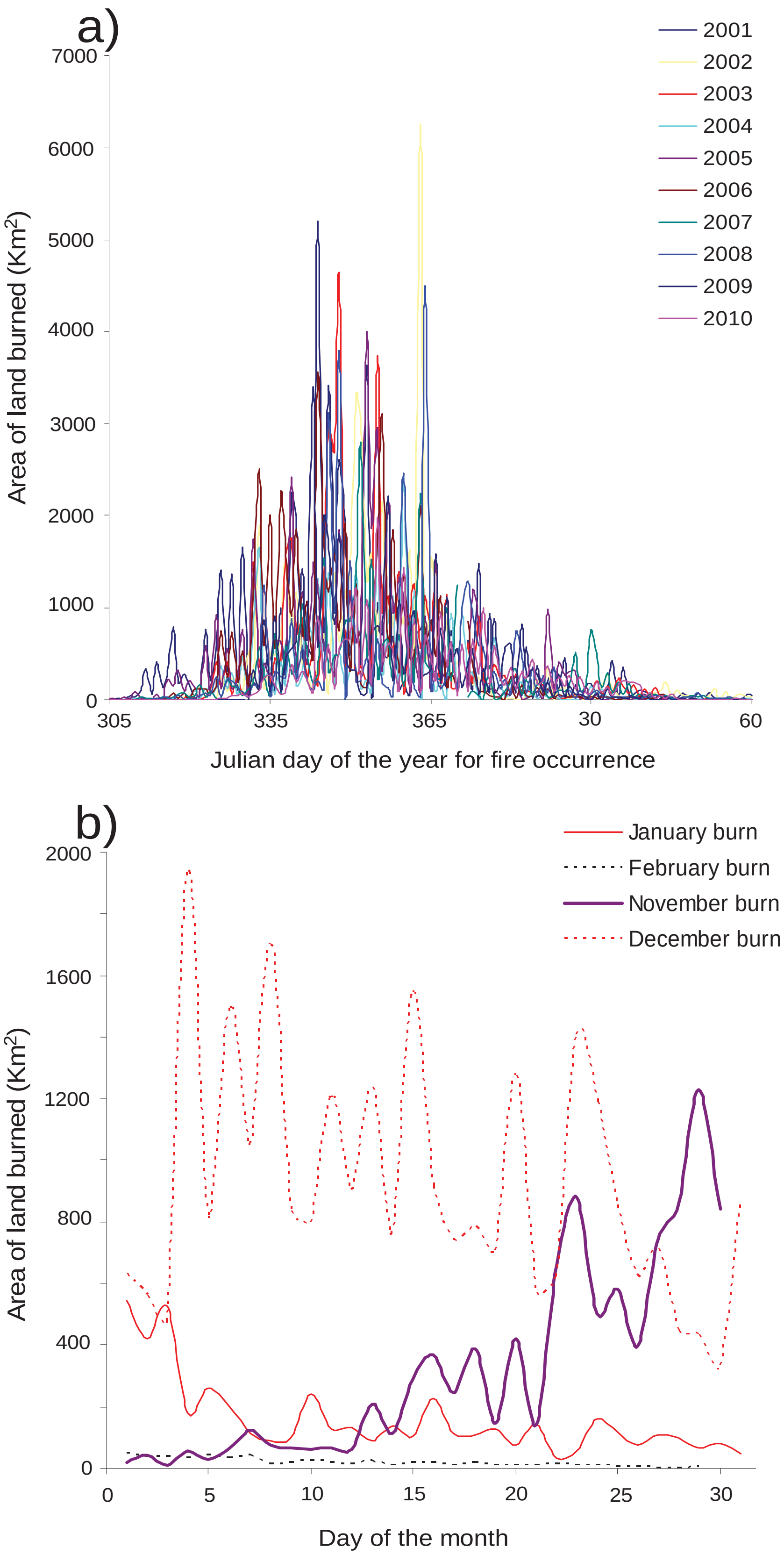

Figure 3.1 Daily burned land cover across the northern region of Ghana over a period of ten years (2001-2010). a): Annual trends in daily fire occurrence. Julian days not shown have no fire incidence. b): Mean daily fire occurrence for the months January, February, November and December showing the period of highest vegetation-burns in the dry season.

The economic services provided by fires to the local communities will render any strict government-oriented fire prevention mechanism difficult to implement. In this regard, fire reduction mechanisms should not aim at fire prevention but should aim at means by which annual fires could still be maintained to provide cyclic economic services but with a reduced impact to environmental productivity.

Across the larger uninhabited interior land areas, however, vulnerability to burn in the mid dry season and the non-existence of human-induced fire controlling mechanisms results in the rapid spread of fires when ignited (Figure 2.2). The area with an unburned fuel load consequently decreases with time, resulting in reduced temporal burns (Figure 3.1a). At the beginning of the year (January), most vegetation is already burned up, and by March there is little or no combustible fuel load left due to burns of the preceding days. Furthermore, the rains begin to set in at this time. These two factors reduce fire occurrence around this time of the year.

3.3.3 Monthly and annual burned area across the northern region of Ghana

About 21%, 68%, 10% and 1% of total annual dry season burns (32-45 thousand km^2) across the northern region of Ghana take place in the months of November, December, January and February, respectively (Figure 3.2). Across the entire country, 24%, 58%, 16% and 2% of the total annual burns (57-79 thousand km^2), respectively, occur in November, December, January and February. The observed trend of monthly burn might be attributed to the combined effect of timing of rainfall and dry season (section 3.3.2). It was anticipated that some farmers may burn shortly before planting so they lose less ash and have less weed problems. This was not, however, observed. The reason could be the temporal reduction of fuel load availability towards the end of the dry season (March), which reduces the spreading ability of vegetation fires and render such fires undetectable by the high-resolution MODIS platform. An observed relatively high percentage burn in January across Ghana (≈16%) compared to January burns across the northern region (≈10%) is because the dry season begins earlier in the northern region.

Also, upon the onset of the dry season (November) larger trees that are found across woody vegetation and across forest areas maintain relatively high moisture content thereby creating a buffering microclimate.

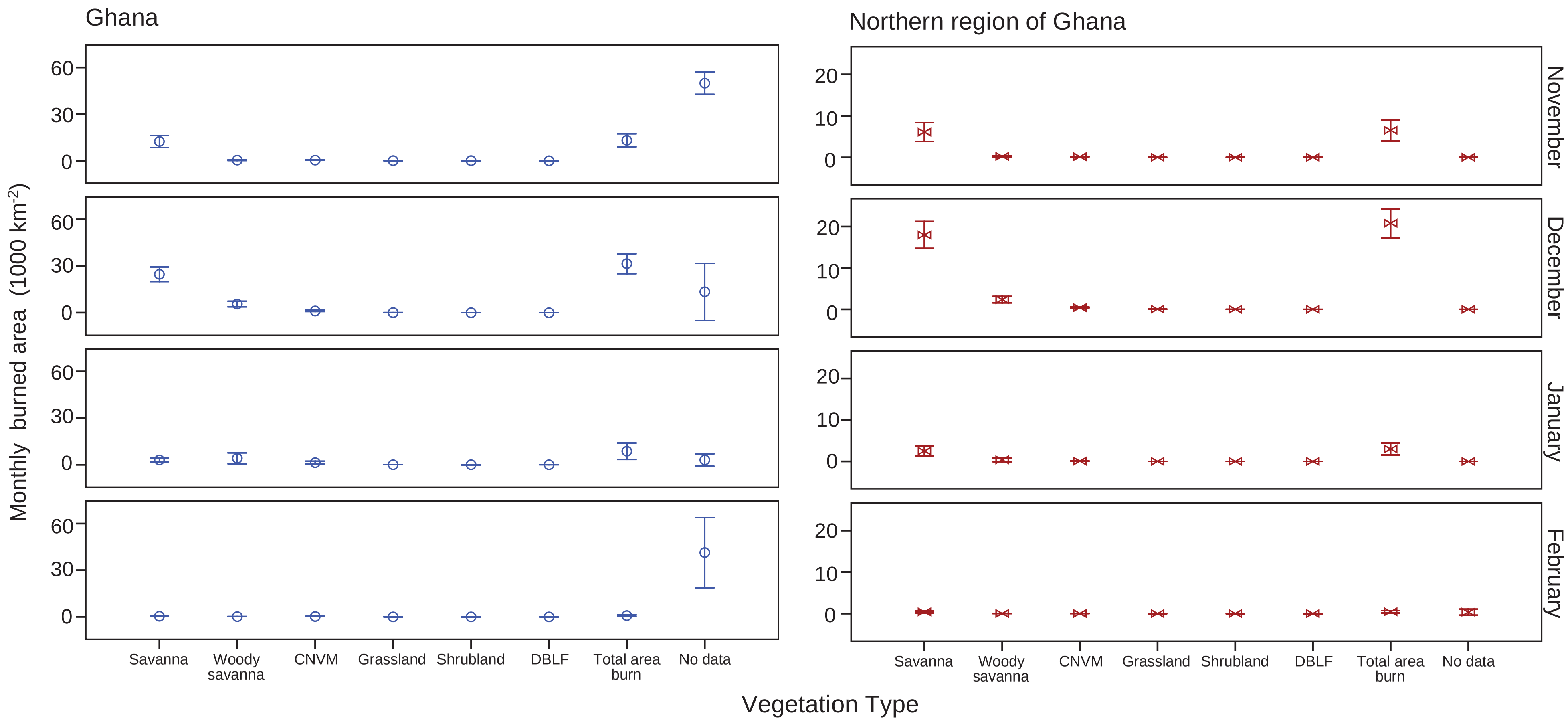

Figure 3.2 Total monthly and total annual burned area of different vegetation types across Ghana (left) and the northern region of Ghana (right) over a period of 10 years (2001- 2010). Points are mean values, bars represent the 95% confidence interval of mean. Total burned area of each vegetation type provided in Appendix 1

This reduces loss of tissue moisture. On the other hand, herbaceous species dry out relatively quickly and become vulnerable to burn. This explains why the northern region generally has relatively higher December burns (≈ 68%) than across entire Ghana (≈ 58%). By middle of the dry season (January) virtually no herbaceous material is left to burn. At same time, the buffering moisture microclimate that might have been created across most woody and forest cover types might be destroyed by the drying effect of the natural harmattan wind. This phenomenon might render woody vegetation vulnerable to burn at this time of the year. Therefore, the higher the relative tree cover, the higher the chance of late burn.

Figure 3.3 shows the total annual burned area (1000 km^2) across Ghana and the northern region of Ghana over a period of 10 years (2001- 2010) with the variabilities in total annual burns from year to year. An average land area of 68 ± 4 thousand km^2 and 37 ± 2.6 thousand km^2 is annually burned across Ghana and the northern region of Ghana, respectively. This constitutes (95% confidence interval of mean) about 25-32% and 46-60% of the total dry land area of Ghana and the northern region of Ghana respectively.

About 53-56% of the total annual burns across Ghana take place in the northern region which constitutes only 29% of total dry land-cover of the country. Annual differences exist in burn areas over the entire country and across the northern region. 2001 was the year with the highest burning activity, where an area of 81, 000 km^2 and 49,000 km^2, respectively, was burned across Ghana and the northern region of Ghana. Reasons for the observed consistent annual decline in burned area from 2001 to 2004 are not known. Year 2004 experienced the lowest burning activity over the 10-year period. An area of 44,000 km^2 and 26,000 km^2 was burned across Ghana and the northern region of Ghana, respectively. Year 2004 may serve as a guide for any survey that intends to identify ways of reducing fires by analyzing the activities that might have resulted in the observed low fire occurrence through field-based interviews. From 2005 to 2010, no patterns of annual vegetation burn were observed.

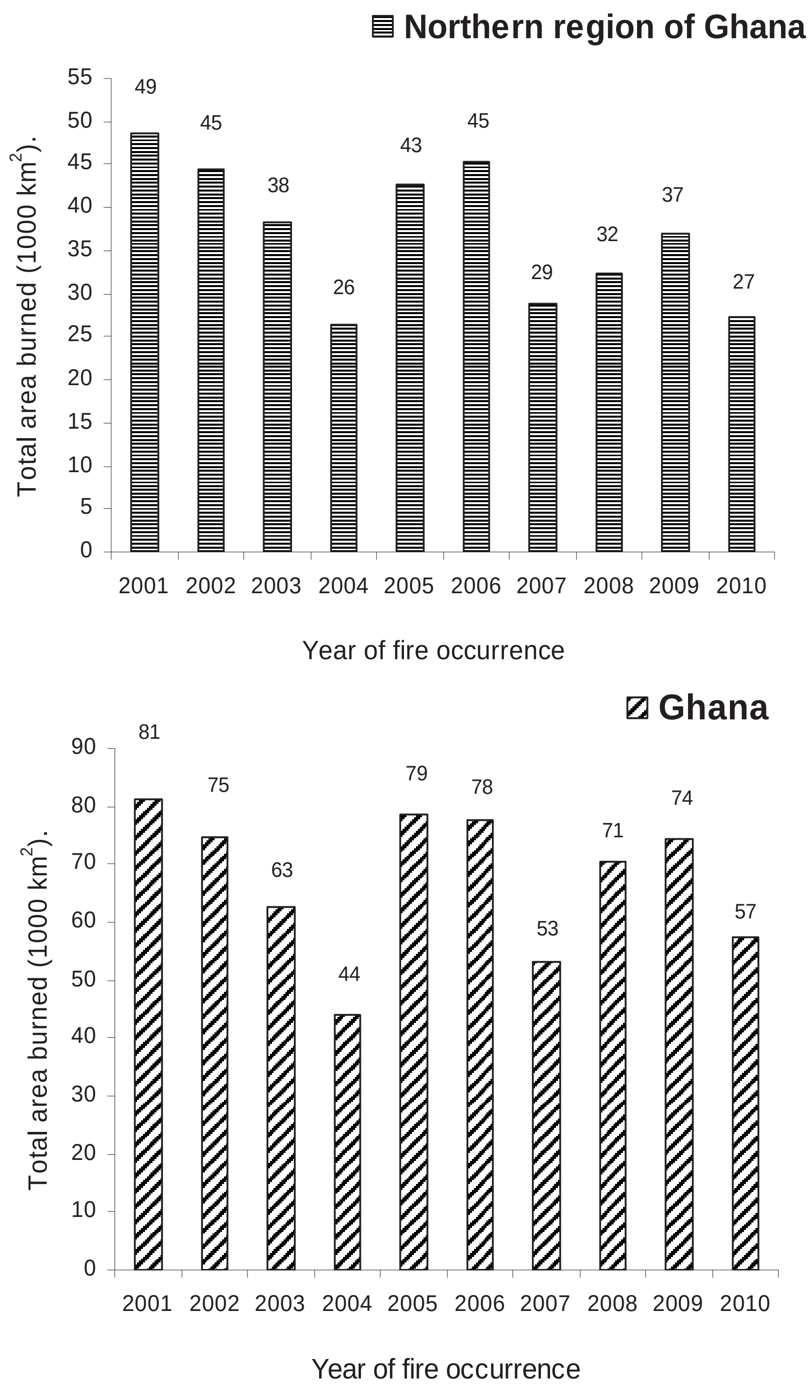

Figure 3.3 Total annual burned area (1000 km^2) across Ghana and the northern region of Ghana over a period of 10 years (2001- 2010) showing the variabilities in total annual burns from year to year

3.3.4 Annual inter-seasonal vegetation burn and agricultural land-use change

The total land area of Ghana amounts to 238,000 km^2 of which 17% are cropped. Figure 3.4 shows the net annual land-use change conversions between cropland and natural vegetation across Ghana from 2001 to 2008.

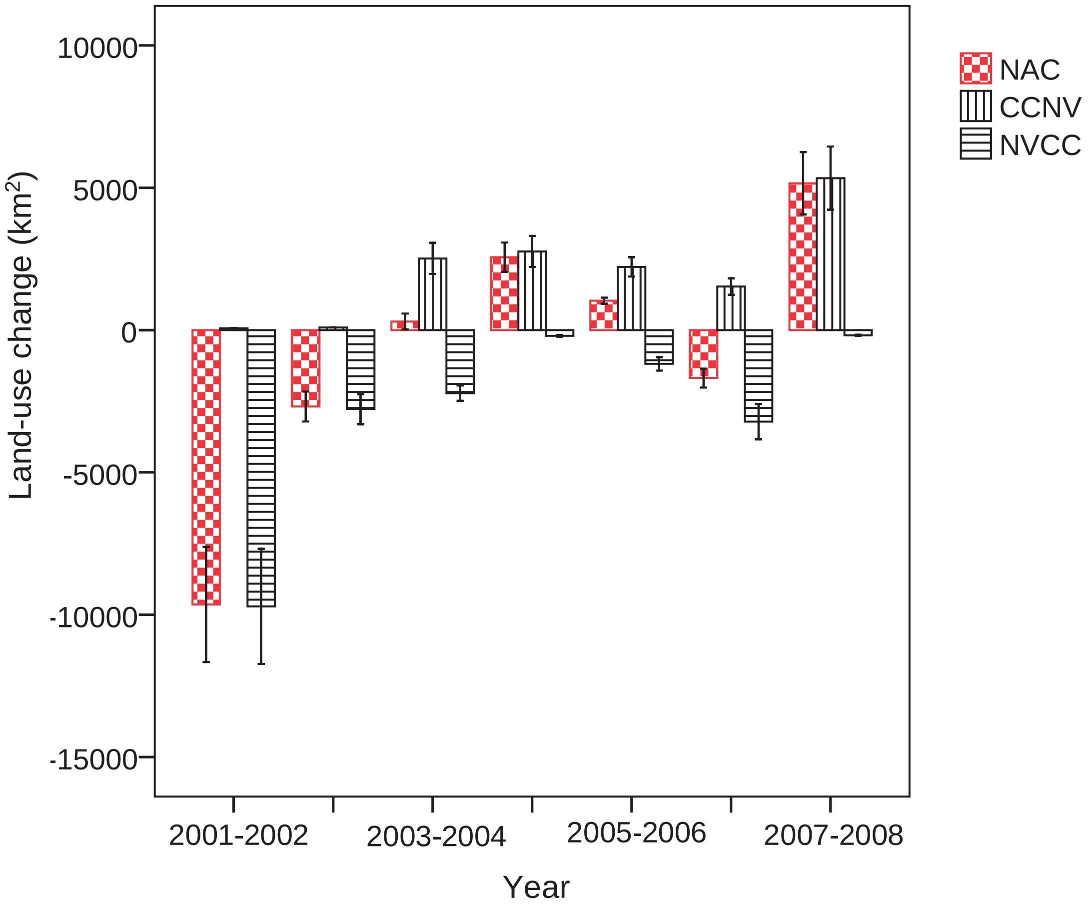

Figure 3.4 Net annual land-use change conversions between cropland and natural vegetation across Ghana from 2001 to 2008. CCNV = croplands converted into natural vegetation (represented by a positive value of land-use change), NVCC = natural vegetation converted into cropland (represented by a negative value in land-use change), NAC = net annual conversion (sum of CCNV and NVCC).

The annual land area of croplands converted into natural vegetation (CCNV, represented by a positive value of land-use change), natural vegetation converted into cropland (NVCC, represented by a negative value in land-use change), and net annual land conversion (NAC, sum of CCNV and NVCC) between cropland and natural vegetation varied from year to year. From 2002 to 2008, the CCNV (mainly evergreen broadleaf forest) was comparatively higher than the NVCC. Conversion into evergreen broadleaf forest serves as important sink to globally emitted carbon suggesting a carbon (C) sequestration trend across Ghana from 2002-2008. This trend corresponds to a global decline in C emissions due to land-use change from 1.3 Pg C to 0.9 Pg C during the period (Global Carbon Project 2010). The highest annual conversion occurred between 2001 and 2002. About 10,000 km^2 of natural vegetation was converted into cropland. The sums of NAC from 2001 to 2008 show that a net land area of about 5,000 km^2 of natural vegetation was converted into cropland over the 8 years. This indicates a trend of high demand (620 km^2 yr^{-1}) of natural vegetation lands for agricultural purposes, mainly food production. The trend calls for a comprehensive look at available land as a limiting factor in issues of food security and sustainability. The 70,000 km^2 of the northern region are more sparsely cultivated (~10%). Savanna, grasslands and shrubland vegetation are the areas most frequently converted into agricultural lands.

Savanna vegetation is the most frequently burned vegetation (Figure 3.2). It constitutes 44,000-60,000 km^2 (75%) and 27,000-40,000 km^2 (88%) of the total annual burned area across Ghana and the northern region of Ghana, respectively (Appendix 1). Woody savanna is the second most vulnerable vegetation (19% of burned area across Ghana and 10% of burned area of the northern region of Ghana). The total annual burned vegetation follows the order of cropland natural vegetation mosaic > grassland > shrubland > deciduous broadleaf forest > mixed forest. About 11% of savanna vegetation, 2 % of shrubland, 5% of woody savannas, and 4% of grassland vegetation that are annually converted into agricultural lands are cleared through bush burning across the country. Susceptibility of these vegetation types to burn make bush burning an easier choice of land preparation for crop production. On agricultural lands (≈40,000 km^2), however, burns for land preparation constituted 1.3% (530 km^2), which is 0.98% of the area of natural vegetation that is annually burned across the country.

The observed trend in natural vegetation cover burn might be attributed to the interplay of cover-type abundance and vulnerability to burn. All things being equal, the more common the vegetation cover, the higher the chance of exposure to fire and the more susceptible it is to burn. Savanna vegetation, being the most extensive cover (Table 3.1) is more exposed to fire and is the most burned vegetation type in all months except in January for Ghana, when woody savanna takes predominance followed by savanna vegetation. The use of area coverage as the sole yardstick for susceptibility of vegetation to burn (Table 3.1), results in the observed order of vegetation type burn (Figure 3.2). This does not take into account the fact that the combustibility of the fuel material at time of fire exposure will also affect the burn.

3.4 Conclusions

Savanna vegetation is most frequently burned cover type due to its relatively high occurrence and vulnerability to burn. The total annual area of land burn is between 46 and 60% (95% confidence interval of mean) of the land cover in the northern region, with savanna vegetation, woody savanna, grassland and shrubland contributing about 98% of the total burn area. Reduced tree growth due to the impact of annual fires may contribute to the establishment of savanna vegetation as the predominant vegetation type across the study area. The period of natural climatic parameters such as rain and onset of the dry season enhance the cyclical accumulation of fuel load that becomes vulnerable to burn upon drying up in the dry season. This annual phenomenon leads to consistent dry season burns starting in the first week of November and ending in the first week of March. Consequently, cyclic annual burning has evolved to be closely associated with the cultural and socio-economic activities of the local people, offering them economic livelihoods by providing goods and services such as for land preparations for agriculture, induced tillering for livestock production and hunting at a relatively low cost. This will render proposed fire prevention mechanisms difficult to implement across the study area. Fire reduction mechanisms should, therefore, not only aim at fire prevention but also at means by which annual fires could still be maintained to achieve the cyclic goods and services they provide: but at a reduced impact on general environmental productivity.

4 BUSH FIRE-INDUCED ANNUAL PLANT NUTRIENT LOSS, CARBON RELEASE AND GREENHOUSE GAS EMISSIONS

4.1 Introduction

Elemental loss due to bush fires may be quantified in two ways. First, for volatile elements like Carbon (C) and nitrogen (N) it can be determined as the product of fuel load and combustion factor/completeness (see equation 1.1). This procedure is based on an assumed linear correlation between loss of volatile elements in the fuel load and the degree of burn. Fuel load and combustion completeness, however, vary for different vegetation types and season of burn because of differences in composition, structure, and rate of consumption during fires (French et al. 2011; Ottmar et al. 2007). Combustion completeness also varies for same fuel load depending on the condition of the fuel load such as the moisture content at time of burn, which in turn varies with season. Differences in seasonal fuel load distribution and seasonal combustion completeness are thus an important factor to consider when one estimates annual elemental losses during vegetation fires.

Second, elemental loss during vegetation fires can be quantified directly on the field from the difference between the elemental content before combustion and that of ash after combustion. This approach estimates the direct losses without reliance on elemental correlations at a given burn completion, and hence is applicable to losses of both volatile elements and losses of the relatively non-volatile elements such as Ca, Mg, and Na. Similar to the former procedure, the direct quantification method captures the inherent difficulties associated with burn completion differences when burns are stratified into seasons/month of occurrence and vegetation type.

During burns, the pathways to local nutrient losses are of two major kinds, i.e., particulate losses (consisting of entrained ash and incompletely burned vegetation fragments) and non-particulate/gaseous losses. Particulate nutrient transfers are defined as nutrients redistributed to soils located within a few kilometers away from the source of loss (Cook 1994; Raison et al. 1985). The non-particulate losses remain in gaseous forms in the atmosphere and are transported by wind currents to other sites several kilometers away from the source of origin. Particulate transfer leads to local losses of soil nutrients. But given that they are eventually deposited within the region, they result in balancing fire-induced nutrient dynamics across the region. The non-particulate losses, however, result in both local and regional losses of nutrients. These nutrient losses may be considered to be the true nutrient losses from the burned regions. Non-particulate nutrient losses are not returned by dry deposition of burned debris/incompletely burned vegetation matter. Though this portion of the total fire-induced nutrient transfer may return to the system through dissolutions in rainfall, the exact return fraction is highly unstable given the duration between the fire season and the onset of the rainy season, and the non-static nature of atmospheric currents on the temporal scale. Non-particulate fire-induced atmospheric elemental transfers may be carried away from the region's atmosphere before the onset of the rainy season. Thus, the transferred fraction that would have dissolved in rain and become deposited into the system is transferred to other sources. If the particulate nutrient losses could be estimated and distinguished from the total losses, this would give an indication of the quantity of nutrients that is locally redistributed in particulate form and the amount that is directly lost during burns.

As mentioned before, the period of annual vegetation burn across the northern region of Ghana is stratified into November, December, January and February (section 3.3.3). The seasonal burned area of each vegetation type (sections 3.3.3 and 3.3.4): provides a foundation to quantify the seasonal and annual elemental loss amounts across the entire region if the gross losses per unit area for existing land-cover types are available and for each season that burns occur.

4.1.1 Problem statement

There is limited data on direct fire-induced gross elemental losses by vegetation type and by season across the study area. Bagamsah (2005) quantified the gross elemental loss values per vegetation type across the study area but only for December and February burns. There is no data on fire-related elemental losses for November and January burns and for the different vegetation types. The relative loss of plant nutrients in particulate and non-particulate forms is not known either. Because fuel load and degree of burn vary with season/month, the lack of elemental loss data for November and January also limits any attempt to estimate total annual nutrient losses across the region.

4.1.2 Aims and objectives

The aims in this part of the study are to:

1. Quantify the gross elemental losses per unit area for each annually burned vegetation type during November (early burn season) and January (late burn season).
2. Model the proportion of the gross annual fire-induced elemental loss that occurs in particulate and non-particulate forms.
3. Estimate a 10-year (2001-2010) annual average of the greenhouse gas emissions (CO_2, CH_4,), local pollutant emissions (CO, NO_x), and gross plant nutrient losses (N, P, K, Ca, Mg, and Na) due to bush fire across the study area.

4.1.3 Research questions

Specific research questions that aim to find solutions to the above objectives are:

1. What is the aboveground fuel load distribution of representative vegetation cover types from November through January?
2. What are the concentrations of N, P, K, Ca, Mg, Na, and C in the aboveground combustible plant materials of representative vegetation cover types before and after (in ash) November and January burns?
3. What are the seasonal/monthly and total annual bush-fire-related elemental transfers/gross losses for each vegetation cover type and across the region?
4. What are the particulate and non-particulate fire-induced elemental transfers during the November and January burns across each vegetation type?
5. What are the seasonal monthly and total annual bush-fire-related gaseous emissions for each vegetation cover type and across the entire region?

4.2 Materials and methods

4.2.1 Burning loss determination

Vegetation cover type identification and selection

From July to October 2010, a field survey of vegetation cover type distribution was conducted across the northern region of Ghana to identify and locate representative burned natural vegetation cover types (burned area > 0.1%, Figure 3.2). The vegetation cover types in the study area described by Bagamsah (2005) were used as a guide. Fuel load sampling and controlled bush burning experiments were undertaken on each representative vegetation cover type (Table 4.1): one during the last week of November 2010 and the other during the first week of January 2011 to conform to the period of highest fire occurrence in these two months (section 3.3.3).

Table 4.1 Geographic locations of the selected most frequent and most burned natural vegetation cover types used to estimate total annual plant nutrient loss and total annual carbon emissions due to vegetation burning. Vegetation types selected based on mean percentage dry cover ≥ 0.3% (Table 3.1) and annual cover burns > 0.1% (Figure 3.2)

Vegetation type	Geographic location	Nearest village
Savanna vegetation	9.12830˚ N /1.20635˚ W	Ntereso
Woody savanna vegetation	9.42502˚ N /0.34616 W	Koljini
Grassland savanna vegetation	9.12850˚ N /1.22151˚ W	Ntereso
Shrubland vegetation	9.20645˚ N /1.08206˚ W	Kusawgu

Land preparation

The sites, each measuring about 75 m by 75 m (Figure 4.1), were adequately fenced.

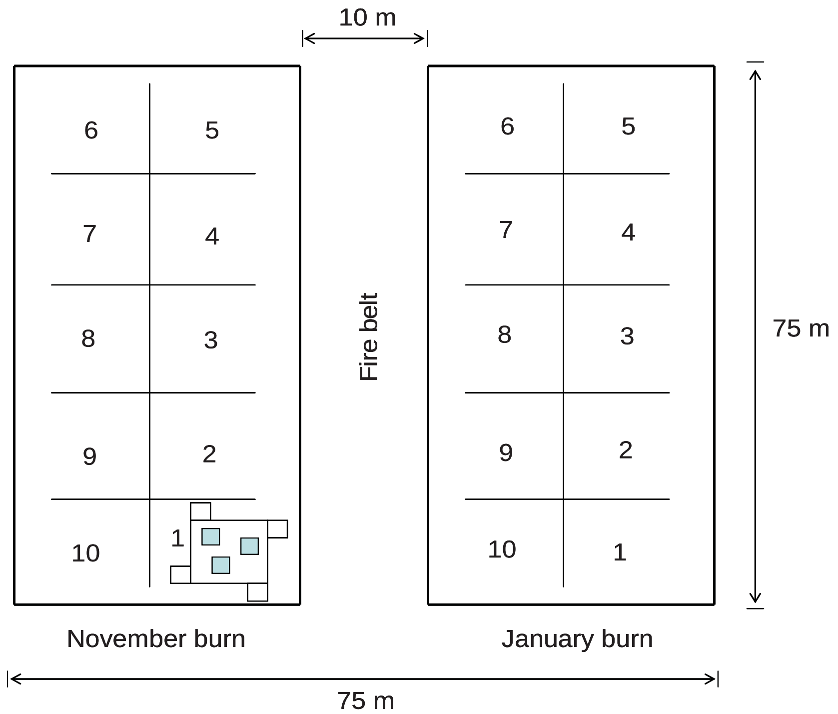

Figure 4.1 General field layout for the controlled burning experiments across the northern region of Ghana during the 2010-2011 burn season. Experiments were undertaken in the last week of November 2010 and the first week of January 2011. Small squares in plot 1 of November burn show plot design for sampling vegetation and combusted ash.

Fire belts, measuring about 10 m in diameter, were created around each site by scrapping all leaves, twigs, debris and combustible materials from the ground and exposing the bare ground. A guard was employed at each site to maintain a 24-hour security, prevent intrusion by herdsmen and their grazing livestock, and protect the four sites from accidental fires from neighboring fields. A 10-m wide fire belt was created to divide each site into two equal halves each about 32.5 m x 75 m (Figure 4.1). One half of each site was used to estimate nutrient loss and carbon release in the November burns and the other half for the January burns. Each field was divided into 10 main burning plots, each measuring 10 m x 10 m (Figure 4.2).

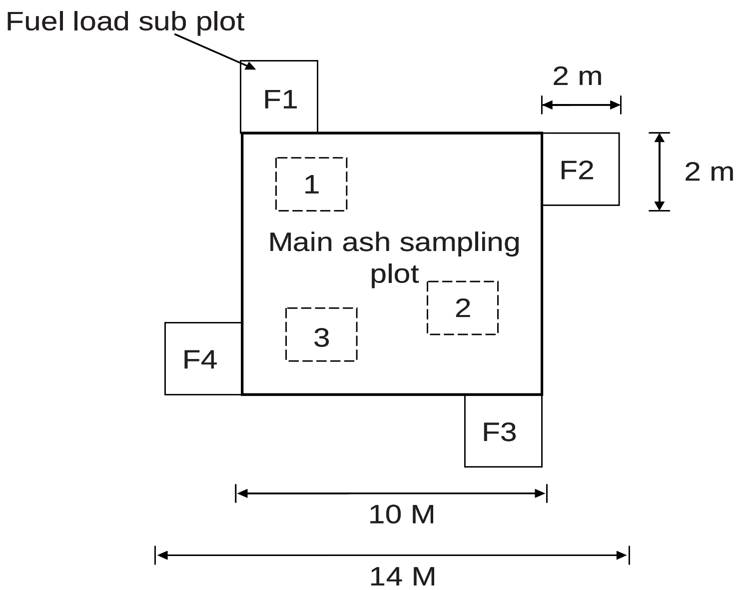

Figure 4.2 Plot design for ash sampling (1, 2, 3) and fuel load (F1, F2, F3, F4) sampling as used in the nutrient loss quantification experiment across the northern region of Ghana during the 2010-2011 vegetation-burn season

Quantification of seasonal fuel load before burns

In this study, fuel load is considered to be any aboveground combustible vegetative material. It excludes stems of standing trees and standing shrubs because they were observed not to burn during fires, but includes combustible attached foliage of shrubs and small trees, standing grass, herbs, fallen leaves, twigs and fallen woody debris, fruits and seeds.

At the four corners of each main burning plot, four 2 m x 2 m wooden quadrats (F1, F2, F3, F4) were used as fuel load subplots to sample the vegetation materials prior to burning (Figure 4.2). The vegetation samples were considered to be representative vegetation on each main burning plot.

All combustible aboveground material in each fuel load sampling subplot was chopped down using a sickle, cutlass, hoe and/or by hand depending on the vegetation cover type and the field condition during sampling. This material was sorted into twigs, herbaceous plants (mainly grasses) and leaves. The samples were weighed in the field after which twigs, leaves and herbaceous plants from the subplots of each main burning plot were bulked. Representative samples of twigs, leaves and herbaceous plants weighing about 200 g each were taken from the bulked samples and air dried in a locally manufactured air drying chamber for a period of one month. Air-dried samples were then oven dried in the laboratory at 90˚C for 48 hrs. Mass of the oven-dried vegetation sample was used for dry mass conversion of the field-weighed samples as fuel load before combustion. The oven-dried samples were then milled for chemical analyses of carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) content.

The moisture content of the vegetation at the time of burn was then calculated as the difference between the field-weighed mass and the oven-dried mass expressed as a percentage of total field-weighed mass.

The carbon/plant nutrient stock of unburned vegetation was calculated for each main burning plot by multiplying the mean fuel load dry matter by the carbon/nutrient concentrations obtained from the chemical analyses.

Estimation of gross seasonal inter-vegetation cover type and annual elemental loss

Plant nutrient/carbon loss in this study is estimated as the difference between plant nutrient or carbon stock in the fuel load before vegetation burns and that of the ash remaining after vegetation burning.

Ash collecting trays (0.75 m x 0.75 m and 2 cm deep) with lids were locally manufactured from iron sheets to collect deposited ash and burned vegetation material during the burns. Three of the trays (Figure 4.2) were randomly put on each main burning plot after removal of all combustible vegetation material under the trays. This combustible vegetation material was placed on the trays in such a way that the edges of the tray were exposed to the consuming fire thus mimicking the natural conditions under which the vegetation gets burned (Figure 4.3). Care was taken to ensure that no soil particles got onto the ash sampling trays as this would have increased the mass of collected ash, affected the nutrient concentration of the collected ash and introduced errors into the set up. Head-fires were set in the direction of the wind.

Figure 4.3 Consuming fire at the woody savanna vegetation land-cover type during the bush fire nutrient loss and carbon emission quantification experiment in November 2010

Duration of burn, wind speed, and temperature of the flames during the burn where recorded. Wind speed was recorded with a VOLTCRAFT BL-30AN anemometer (measuring range 1.1-30 m s^{-1}, error 0.01 m s^{-1}). Flame temperature was recorded with a VOLTCRAFT IR 1000-30D infra-red thermometer (measuring range -50 to +1000 °C).
The ash trays were covered with lids immediately after the burn to prevent the ash from being blown off by wind. The covered trays were left overnight on the field to cool down. The ash samples were collected in the early morning of the following day when the wind speed was relatively low. The burned samples in each tray were separated into ash, unburned leaves, unburned twigs and unburned herbaceous plants (Figure 4.4) and weighed. The mass of unburned leaves, twigs and herbaceous plants was deducted from the mass of fuel load, i.e., leaves, twigs and herbaceous plants, respectively, in order to calculate the quantity of each vegetation part that was combusted during the burn.

The ashes collected from each plot were bulked to give total ash collected from each main burning plot. Total ash collected was weighed in the laboratory with a sensitive weighing balance (KERN CB 3K0.5N), sieved and fractionated into fine ash (<1 mm) and coarse ash (>1 mm). Coarse and fine ash fractions from each main burning plot were then analyzed for C, N, P, K, Ca, Mg, and Na in the soil chemistry laboratory of the Savanna Agricultural Research Institute (SARI), Nyamkpala, northern region, Ghana.

Figure 4.4 Field pre-processing of burned vegetation into unburned parts (unburned herbaceous plants, unburned twigs and unburned leaves) and ash component

Carbon/plant nutrients in the fractionated ash were calculated for each main burning plot by multiplying the mass of fractionated ash (fine ash or course ash) by the carbon/nutrient concentrations obtained from each ash fraction. Total carbon (amount per unit area)/plant nutrients in the ash of each plot and for a vegetation type was calculated for each month as:

$$V = M + Q \tag{4.1}$$

where V = total carbon (amount per unit area) /total plant nutrient left in the ash, M = the carbon/plant nutrient left in fine ash in the vegetation burned in a given month (amount per unit area), Q = carbon/plant nutrients left in coarse ash (amount per unit area).

Gross carbon/plant nutrient loss by each plot in a given month and vegetation type was calculated as:

$$EL = T - V \tag{4.2}$$

where EL = elemental loss per unit area (C, plant nutrients), T = Elemental content per unit area (C, plant nutrient) of unburned vegetation, V = elemental content (per unit area) of ash in the plot.

EL, T, V, M and Q for each vegetation type (mean ± standard error) in a given month were then estimated as the average of values obtained from the 10 representative burning plots.

For fields identified as cropland/natural vegetation mosaic where about 2% and 5.6% of total annual burns across the northern region and across Ghana occur, respectively (Figure 3.2), field reconnaissance observations indicated that most parts of the field that burned constituted natural grasslands and stovers of harvested grassy crops such as maize, rice, sorghum and millet, while the other parts constituted crops such as yam and cassava. Based on this observation, 50% of the burns on these fields were estimated to have similar elemental loss values to those quantified for grassland vegetation. The other 50% was not considered in the study because it involved varying crop types with different elemental constituents that render predictions extremely unreliable. This introduced, respectively, an estimated error of 2-3.2% and 0.7-1.2% of the total burned area across Ghana and the northern region of Ghana.

Estimation of particulate nutrient transfers and non-particulate nutrient losses

Particulate and non-particulate fractions of the gross elemental transfers were modeled by considering all fire-induced Ca losses as an indicator of particulate losses. Since the volatilization temperature of Ca is high at 1484 ˚C (Cook 1994) and was not exceeded during burns, losses of Ca were attributed to direct fire-induced ash/particulate transfers only.

Ca losses could thus be given as:

$$L_{Ca} = C_{Ca} \cdot L_{Ta} \qquad (4.3)$$

where L_{Ta} is the mass load of transferred particulate ash (kg km^{-2}),
L_{Ca} = loss of Ca (kg km^{-2}) = quantity of Ca transferred to the atmosphere in particulate form, C_{Ca} = concentration of Ca in the ash after burns = concentration of Ca in the particulate transferred ash.

The quantity of fire-induced entrained ash (L_{Ta}) is thus given as:

$$L_{Ta} = (L_{Ca}/C_{Ca}) \qquad (4.4)$$

Particulate transfer of the other elements: (C, N, P, K, Mg and Na) was then estimated as:

$$P_{TE} = (L_{Ta} \cdot Conc_{element}) \qquad (4.5)$$

and the non-particulate elemental transfers (NP_{TE}) as:

$$NP_{TE} = \text{gross elemental loss} - P_{TE} \qquad (4.6)$$

where $Conc_{element}$ = concentration of the given element in the ash.

4.2.2 Estimation of gross annual plant nutrient loss and greenhouse gas emissions

For the months December and February, field-determined, fire-induced elemental loss values per unit area across each vegetation type (Bagamsah 2005) were used. Total annual nutrient transfers and emissions were then estimated as:

$$NT = \sum_{pk} (A \cdot EL) \tag{4.7}$$

$$E = \sum_{p} (EF \cdot (A_k \cdot CFL_k) \tag{4.8}$$

CFL = the factor FL·C in equation (2.1) (4.9)

where NT is direct nutrient transfer to the atmosphere due to burn (kg), p is the vegetation cover class (savanna, shrubland, grassland, woody savanna), k is the month in the fire season (November, December, January, February), A is the burned area (km^2), EL is loss in given element in fuel load due to burns (kg km^{-2}, given by the elemental content of fuel load before burn minus elemental content of ash after burn), E is emission of a given greenhouse gas (g), EF is the emission factor (g molecular emission kg^{-1} combusted dry fuel load; same factor used for all months) (IPCC 2006; Akagi et al. 2011; Wiedinmyer et al. 2011), and CFL is the quantity of fuel load combusted (kg m^{-2}).

4.2.3 Chemical analyses of plant tissue and ash

Chemical analyses followed recommended procedures (IITA 1979). Carbon was determined by loss in mass upon ashing and determined in the Soil Chemistry Laboratory of the Soil Research Institute of Ghana. N, P, K, Ca, Mg, and Na in plant and ash tissue were analyzed in the soil chemistry laboratory of the Savanna Agricultural Research Institute, Nyamkpala. Total N was determined by the Kjeldahl procedure; P, K, Ca, Mg, and Na were analyzed through wet acid digestion followed by individual element analyses, P by the vanado-molybdate calorimetry method, Ca and Mg through titration, and K and Na by flame photometry.

4.2.4 Statistical analyses

Calculated data are reported in either of two formats: Mean ± standard error of mean when statistical comparisons are made, or the 95% confidence interval of mean for estimated values. In situations where statistical data from other sources were used for further computation, the 95% confidence intervals were computed as mean ±standard error of mean. Statistical differences in means of three or more groups (e.g., nutrient content/concentration by vegetation part/type) were analyzed using analyses of variance (ANOVA), while the difference between two groups (e.g., nutrient concentration/content of fine and coarse ash) were analyzed using t-testing, both at an alpha level of 0.05. Post-hoc tests were run with the Duncan's multiple range test to determine the direction of variation and which classes differed. Duncan's multiple range test was used because the parameters being compared were not factorial in nature and did not correspond to several levels of a continuous variable.

4.2.5 Limitations and uncertainties associated with elemental losses and emissions

Besides the uncertainties in identification of burn areas and vegetation types (section 3.2.2), there are unquantifiable uncertainties associated with aspects of the nutrient loss/emission estimates. The lengths of preceding burns affect the accumulated fuel load. The allotted fuel load will not be representative of the prevailing condition in such situations. Differences in plant growth across similar vegetation types also affect elemental accumulations, which in turn affect the total elemental losses and emissions. Uncertainty due to fuel load quantification for each vegetation type, though reduced by using confidence statistics, remain, as the true fuel load value for a given vegetation type at a given time may equally falls above or below the quantified range. The only difference being the less likelihood (5%) that they fall above or below the estimated range.

Combustion completeness is the fraction of fuel load exposed to fire that actually gets burned (Silver et al. 2011). Uncertainties arising from burn completion are reduced by stratifying burns into vegetation cover types and month/season of burn. This stratification does not, however, prevent uncertainty due to burn completion that occurs even within the same vegetation type, as each vegetation type has differing degrees of burn across different locations at different times. This uncertainty was reduced to a minimum by only using data on actual element loss (difference between element content before burn and element content of ash after burn for each month and vegetation type) instead of using original fuel load and assumed burn completion per vegetation type (Korontzi et al. 2003).

The emission factors used in this study also introduce uncertainties to the estimation. Emission factors for each vegetation type and by month of fire occurrence were generally not available. This compelled the use of the same factor for the year on a given vegetation cover. Computing parallel scenario maximum and minimum confidence statistics from annual sampled values that are reported for similar vegetation types reduces this uncertainty but does not eliminate it. Due to differences in fuel load distribution within a given vegetation type at different times within the same month, which influence the temperature of combustion and hence emission (Urbanski et al. 2008), this uncertainty remains even if emission factors had been available for each vegetation type and month.

In general, it is difficult to assign a quantitative variable to the unmeasured uncertainties in the fire-induced emissions and hence absolute accuracy in the overall estimate largely due to inherent limitations of input parameters that could lead to large uncertainties. Uncertainties associated with the estimations were generally reduced by use of quantified data only, and by use of the 95% confidence interval of the mean for all input data (elemental losses, burned area and emission factors). This was done to estimate parallel scenarios for minimum and maximum estimates. Lower-bound and upper-bound elemental losses/emissions were estimated separately from the lower bound-input and upper bound input data, respectively. Use of this procedure resulted in an error of 0.1% when compared with results obtained from a simulated sample population where each sample has unique elemental loss values, burned-area values and emission-factor values. This suggests comparable results from the two procedures.

4.3 Results and discussion

4.3.1 Physical parameters during burn

Variation in duration of flame burn was anticipated across the different vegetation groups because of the differences in composition of vegetation structure, variation in wind direction during burn, and variation in wind speed during burn (Table 4.2). Generally, the higher the herbaceous composition (as in grassland and woody savanna vegetation types), the shorter the duration of flame burn. Across the same vegetation type, high moisture content at time of burn impedes the burn (Towne and Kemp 2008). In a fairly dried condition like in the November burn situation, as long as there is a continuum of adequately dried combustible state material, this impediment does not completely stop the burn and hence prolongs the duration of burn.

Table 4.2 Duration of burn, wind speed during burn and temperature of burn during controlled burning loss experiment in November 2010 and January 2011 across the northern region of Ghana

Nov.	Vegetation	Duration of flame burn (min)	Wind speed (m s^{-1})		Temperature of burn (˚C)	
			Mean	Maximum	Mean	Maximum
	Savanna	13	0.84	2.16	492	814
	Woody savanna	10	0.51	1.67	675	791
	Grassland	7	0.68	1.8	601	807
	Shrubland	27	0.9	2.33	531	868
Jan.						
	Savanna	17	0.87	1.96	496	898
	Woody savanna	8	1.08	3.96	487	693
	Grassland	8	1.01	4.36	235	735
	Shrubland	9	0.95	3.87	275	790

The duration of burn was in the order grassland<woody savanna in both months (Table 4.2). The different relative duration between savanna vegetation and shrubland vegetation in November and January might be due to interplay of relative vegetation composition and the moisture content of these two vegetation types at the time of burn. The extended flame burn period in November for shrubland vegetation is due to the high amount of leafy components at this time, which promotes vertical burns and limit horizontal burn, a phenomenon that extends the period of burn. In January, however, most of the leaves in shrubland vegetation might have fallen to the ground thereby reducing vertical burns and limiting burns to horizontal spread and consequently reducing the flame burn period. A similar burn pattern as in shrubland burns was observed for burns on savanna vegetation. However, the relatively high amount of grassy components of savanna vegetation compared to shrubland vegetation enhances rapid horizontal spread that results in a reduced flame burn period. In January, however, savanna vegetation has the longest flame burn period due to higher amounts of adequately dried twigs that promote combustion at a relatively slow rate.

Mean flame temperatures ranged from 492˚C to 675˚C in November burns and 235˚C to 496˚C in January burns (Table 4.2). Besides for savanna vegetation, mean flame temperature for all vegetation types was higher for November than for January burns. This is attributed to relatively high vegetation moisture contents in November compared to January (Table 4.3, see also Appendix 2 for comparison of the moisture content of leaves, herbs/grass and twigs).

Table 4.3 Pairwise t-test of statistical difference in fuel load distribution, ash load distribution, and losses in mass between early (November) vegetation-burns and late (January) vegetation-burns for different vegetation cover types across the northern region of Ghana during the 2010-2011 fire season. n = 10. Means and standard error of means provided in Table 4.4, and Tables 4.11 to 4.17.

	Savanna		Woody savanna		Grassland		Shrubland	
	t	Sig. level	t	Sig. level	T	Sig. level	t	Sig. level
Fuel load								
Fuel load	1.6	0.142	1.2	0.260	-1.0	0.327	0.0	0.999
N	3.3	0.011	3.4	0.008	0.3	0.788	3.5	0.007
P	-1.4	0.190	2.4	0.041	-3.9	0.003	0.3	0.790
K	2.5	0.039	2.2	0.056	-3.4	0.008	-2.9	0.019
Ca	2.8	0.022	1.3	0.236	-0.7	0.512	0.8	0.463
Mg	1.4	0.191	1.1	0.304	-5.7	<0.001	1.9	0.085
Na	2.3	0.049	2.1	0.064	0.2	0.839	0.9	0.395
C	1.2	0.246	1.1	0.290	-1.2	0.252	0.1	0.948
%moisture	3.9	0.004	2.6	0.031	1.6	0.144	6.0	<0.001
Ash/ash nutrient load								
Ash	7.8	<0.001	4.3	0.002	-2.9	0.018	2.4	0.040
N	6.5	<0.001	3.3	0.010	-0.5	0.657	2.6	0.028
P	2.8	0.024	4.0	0.003	1.1	0.294	2.6	0.027
K	3.6	0.007	2.9	0.021	-5.6	<0.001	3.7	0.006
Ca	7.4	<0.001	4.1	0.003	-3.2	0.010	2.1	0.073
Mg	5.5	0.001	3.9	0.003	-2.3	0.049	2.3	0.044
Na	2.6	0.030	1.2	0.274	-6.8	<0.001	-0.6	0.580
C	5.8	<0.001	3.0	0.014	-1.9	0.096	0.1	0.954
Fuel load/elemental loss								
Fuel load	0.5	0.661	0.7	0.515	-0.7	0.494	-1.0	0.356
N	3.1	0.014	3.3	0.009	0.3	0.773	3.1	0.012
P	-2.7	0.027	1.7	0.116	-4.6	0.001	-0.6	0.588
K	1.1	0.322	0.5	0.644	-0.7	0.497	-5.3	0.001
Ca	0.2	0.810	0.0	0.980	0.1	0.952	-0.8	0.449
Mg	1.9	0.090	-0.2	0.862	-4.7	0.001	0.5	0.612
Na	1.6	0.139	1.9	0.093	1.0	0.325	1.1	0.283
C	0.9	0.395	0.9	0.411	-1.2	0.277	0.1	0.955

A moisture difference was observed across savanna, woody savanna, and shrubland vegetation.

The biomass combustion process generally involves distillation, ignition, pyrolysis, flamming + pyrolysis, glowing + pyrolysis (smouldering), glowing, and extinction (Lobert and Warnatz 1993; Yokelson et al. 1997). Moisture in wood needs to be vaporized before combustion and wood pyrolysis takes place. The high tissue moisture in the early season acts as sink for heat thereby increasing the thermal inertia and consequently the temperature of the wood burn. The comparatively high moisture content of twigs during the late season compared to that of herbs and leaves (Appendix 2) reduces the comparative combustion of twigs, which in turn reduces the impact of annual fires on established trees.

Decomposition of specific compounds during fires is characterized by the temperature of the burn (Libra et al. 2011). For instance, hemicelluloses decompose at temperatures between 200 and 400˚C, cellulose at temperatures between 300 and 400˚C, while the more stable lignin components of plants typically decompose at temperatures between 180 and 600˚C (Groenli et al. 2002). Volatilization temperature of N is about 200˚C, P is 777˚C, K is 760˚C, Ca is 1484˚C, Mg is 1107˚C and Na is 880˚C (Gray and Dighton 2006; Grier 1975; Caldwel et al. 2002; Ranalli 2004; Miller et al. 2010). Recorded mean temperature across all vegetation types was higher than volatilization temperature of N. The maximum temperature of combustion influences the pyrolitic reaction during the burn (Downie et al. 2009; Libra et al. 2011). In analyses of ~900˚C ash Ca for various plant tissues, Misra et al. (1993) attributed a sharp increase in Ca concentration to the dissociation of potassium carbonate and the subsequent volatilization of potassium oxide leading to a decline in K concentration and an increase in ash Ca concentration. Except for the January burns across grassland and woody vegetation, the recorded maximum burn temperatures were just above the volatilization temperatures of P and K, and below the volatilization temperatures of Ca, Mg and Na. Consequently, N was likely volatilized during the burns across all vegetation types. Phosphorus and K volatilize during vegetation burns but only during the time that maximum burn temperatures exceed their respective volatilization temperatures. Sodium may volatilize in the January burns across the savanna vegetation but only during the duration of burn when maximum burn temperatures exceed 880˚C.

Time and temperature of burn influence product characteristics (Landais et al. 1994). Consequently, the longer the duration of burn at temperatures above the respective volatilization temperatures, the higher the quantity of P, K and Na volatized in the given burn condition. Ca and Mg are, however, not volatilized during burns across the region.

4.3.2 Fuel load distribution before burn and ash distribution after combustion

Seasonal differences in fuel load and ash distribution

Except for grassland vegetation, combusted fuel load and nutrient load are generally higher in November compared to January (Table 4.3 and Table 4.4).

Table 4.4 Fuel load before combustion, ash load remaining after combustion and net loss in mass during bush fires by representative vegetation cover types across the northern region of Ghana in November 2010 and January 2011. Values are means with standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Combusted fuel load (Mg km^{-2})										
Leaves	49^{b}	18^{BC}	33^{b}	65^{B}	3^{b}	0^{C}	114^{a}	253^{A}	0.001	<0.001
	(30)	(5.5)	(9)	(8)	(2)	(0)	(18)	(40)		
Herbs	409^{a}	386^{B}	374^{a}	205^{C}	474^{a}	542^{A}	153^{b}	76^{D}	0.001	<0.001
	(47)	(34)	(68)	(26)	(59)	(34)	(34)	(17)		
Twigs	41^{b}	23^{AB}	8^{c}	57^{A}	3^{c}	8^{B}	84^{a}	22^{AB}	<0.001	0.049
	(8)	(10)	(3)	(21)	(1)	(5)	(11)	(3)		
Total	499	426^{B}	416	326^{B}	480	550^{A}	351	350^{B}	0.347	<0.001
	(66)	(32)	(70)	(27)	(58)	(45)	(36)	(27)		
Mass of ash after combustion (Mg km^{-2})										
Fine	81^{a}	45^{B}	57^{b}	39^{B}	26.8^{c}	47^{B}	88^{a}	66^{A}	<0.001	<0.001
	(6)	(3)	(6)	(3)	(4)	(4)	(9)	(4)		
Coarse	19^{b}	3^{B}	33^{a}	10^{B}	5^{c}	9^{B}	33^{a}	22^{A}	<0.001	<0.001
	(2)	(1)	(5)	(2)	(1)	(23)	(5)	(4)		
Total	100^{a}	48^{B}	91^{a}	49^{B}	32^{b}	56^{B}	121^{a}	89^{A}	<0.001	<0.001
	(6)	(4)	(11)	(4)	(5)	(5)	(14)	(4)		
Loss in mass during combustion										
Mg km^{-2}	399	378^{B}	325	277^{BC}	448	494^{A}	230	262^{C}	0.055	<0.001
	(62)	(31)	(66)	(28)	(56)	(46)	(41)	(29)		
%	78^{b}	88^{A}	78^{b}	84^{A}	93^{a}	89^{A}	65^{c}	73^{B}	<0.001	<0.001
	(2)	(1)	(7)	(2)	(1)	(1)	(7)	(2)		

Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

Literature values on combusted fuel loads, ash loads and consequent losses during November and February burns across each vegetation type (Bagamasah 2005) are provided in Table 4.5 for comparison. Across savanna, woody savanna and shrubland vegetation types, the quantities of ash remains are higher for early burns than for late burns, while across grassland vegetation the quantity of late burn ash is higher than in the early burn (Table 4.3 and Table 4.4). The high November ash and ash nutrient content compared to January is attributed to a relatively active plant growth period due to the comparatively high moisture availability in November (section 4.3.1).

Table 4.5 Combusted fuel load, ash load distribution after combustion, and losses in fuel load during December (2002) and February (2003) burns for representative vegetation cover types across northern region of Ghana. Data adopted from Bagamsah (2005). n = 10, values are means, standard error of mean in brackets beneath the mean.

	Savanna		Woody savanna		Grassland		Shrubland		DBLF	
	Dec	Feb	Dec	Feb	Dec	Feb	Dec	Feb	Dec	Feb
Combusted fuel load (Mg km^{-2})										
Herbs	518	169	503	513	623	576	327	158	488	237
	(46)	(15)	(52)	(60)	(25)	(33)	(23)	(10)	(33)	(24)
Leaves	29	111	52	138	11	196	74	148	42	111
	(3)	(14)	(8)	(18)	(3)	(14)	(16)	(16)	(8)	(14)
Twigs	57	1	69	53	23	10	103	18	64	34
	(18)	(0.8)	(16)	(14)	(4)	(3)	(23)	(2)	(19)	(12)
Total	605	281	651	703	674	780	499	336	608	379
	(55)	(13)	(58)	(64)	(29)	(40)	(45)	(19)	(42)	(29)
Ash load(Mg km^{-2})										
Fine	24	78	29	92	73	57	34	62	62	72
	(1)	(8)	(5)	(11)	(6)	(5)	(2)	(7)	(6)	(4)
Coarse	28	39	29	42	51	21	11	34	27	62
	(3)	(6)	(4)	(4)	(3)	(4)	(1)	(6)	(3)	(2)
Total	52	117	58	134	124	78	45	97	88	98
	(3)	(1)	(9)	(2)	(8)	(8)	(3)	(13)	(9)	(8)
loss in fuel load (Mg km^{-2})										
	552	164	593	569	550	702	453	239	520	282
	(57)	(19)	(58)	(68)	(34)	(41)	(45)	(27)	(41)	(35)

Dec = December, Feb = February, DBLF = Deciduous broadleaf forest

The high moisture results in higher tissue elemental content due to efficient elemental uptake by plant roots (Misra and Tyler 2000). In January, however, the plants become relatively dry and less active. A comparative reduction of soil moisture for nutrient transport results in water stress conditions that reduce root elemental uptake by the plant. Consequently, element accumulation in plant tissues reduces, resulting in a relatively low ash elemental content. The higher amount of ash in November than in January is also attributed to the moisture content, which limits ignition and impedes burning, resulting in formation of more solid char products of incomplete combustion (Libra et al. 2011; Trollope and Trollope 2002). The result is the formation of patches of burned and unburned vegetation that inhibit late burn occurrence, enhance the sustenance of wildlife, and promote tree seedling growth and establishment for carbon capture and storage.

Grassland and shrubland generally have higher elemental losses during January burns than during November burns, while savanna and woody savanna vegetation has higher losses in November than in January. This observation is attributed to a higher content of smaller twigs in the savanna and woody savanna vegetation that dries out relatively quickly and facilitates early burns in these vegetation types, while the shrubland vegetation consists of relatively larger and moist twigs that are difficult to ignite and burn at the beginning of the dry season and hence require some time to adequately dry before combustion.

Total fuel load distribution

Unless otherwise stated, field-quantified fuel load, ash and elemental estimates are comparable to those obtained by Bagamsah (2005) across the study area. The mean of total combusted fuel load ranges from 351 Mg km^{-2} across shrubland vegetation to 499 Mg km^{-2} across savanna vegetation during the November burn and 326 Mg km^{-2} across woody savanna vegetation to 550 Mg km^{-2} across grassland vegetation during the January burn (Table 4.4). The fuel load estimated in this study falls within the 200-519 Mg km^{-2} estimated across various savanna systems of Africa (Shea et al. 1996; Laclau et al. 2002; Bourliére and Hadley 1983) and across the study area (Saamak 1999; Bagamsah 2005). The grass fuel load values across grasslands are comparable to the 545 Mg km^{-2} estimated for invasive *Andropogon gayanus* cover across Australia by Rossiter-Rachor et al. (2008). Total fuel load values of 480±58 Mg km^{-2} and 550±45 Mg km^{-2} across grassland vegetation is also comparable to the values for rice straw fuel load of 85.6-634.4 Mg km^{-2} (Kanokkanjana et al. 2011). Contrary to the anticipated variations in seasonal amount of combusted fuel load, there was no significant difference in values between November and January (Table 4.3). The relatively high November values compared to those in January are attributed to comparatively high plant productivity due to favorable moisture conditions (Van de Water and North 2011).

Shrubland vegetation, though it has a comparatively high general vegetation cover, showed the lowest total combusted fuel load of 350 Mg km^{-2} because it consisted of higher amounts of relatively moist and difficult to burn larger twigs (Gorte 2009), leaves, and a comparatively lower amount of easy to burn grassy components. On the other hand, grassland savanna showed the highest values because it consisted solely of easy to burn grasses that are completely combusted during the burning process. The high share of grasses in savanna and woody savanna vegetation also resulted in the high combusted fuel load amounts in these vegetation types.

Combusted twig fuel load

Amount of combusted twigs varied among the vegetation types and the month of burn. Shrubland vegetation had the highest combusted twigs of 84 Mg km^{-2} and 22 Mg km^{-2}, respectively, during November and January burns. Grassland savanna had the lowest values. High January values of 57 Mg km^{-2} in woody savanna could be attributed to broken parts of trees that get dried up and fall to the ground contributing to the total combusted fuel load. Though the amount of early season combusted twigs is comparatively higher than in the late season across savanna, grassland and shrubland vegetations, the opposite is the case across woody savanna vegetation and is attributed to the height of the twig material at time of combustion. In the early fire season, most twigs across woody savanna vegetation are still relatively moist and attached to woody plants at heights away from ground level. Fires in the early burn season will thus not easily access such plant parts.

In the late dry season, however, most twigs get adequately dried out and in some cases break off the woody plant and fall to the ground. This increases accessibility to fire and renders twigs of woody savanna vegetation relatively vulnerable to combustion by late season fires. A comparable combusted twig distribution of 41 Mg km^{-2} and 23 Mg km^{-2}, respectively, across savanna vegetation in November and January was anticipated. In November, the small twigs and shrubs get adequately dried to be combusted.

Combusted herbaceous/grass vegetation

Herbaceous vegetation is the most burned plant material across all vegetation types except across shrubland vegetation in January, where leaves are the most burned plant materials per unit burned area. Herbaceous materials are most easily combusted because of their relatively high combustibility, enhanced by adequate aeration space, fuel material, and package of fuel stock. These properties allow quick drying up compared to leaves and twigs and facilitate their combustion. Besides, leaves and twigs across woody savanna vegetation are mostly combusted only if they happen to fall to the ground. Though this is not the case across shrubland and savanna vegetation where plant-bound leaves can be combusted, this results in a comparatively lower amount of burnt leaf and twig components. Across grasslands, there may be no leaf or twig cover at all, in which case only herbaceous materials are combusted during fires. Fallen leaves/twigs and combusted plant-bound leaves/twigs are also relatively less in quantity than combusted herbaceous materials.

The quantities of herbaceous materials combusted during early burns are greater than those combusted during the late burns across all vegetation types except across grassland vegetation. Combusted herbaceous materials range between 153 Mg km^{-2} and 474 Mg km^{-2} in November burns to between 76 Mg km^{-2} and 542 Mg km^{-2} during January burns. The observations show a high range in grass fuel load across the landscape with values comparable to those reported by Shea et al. (1996) of 131-311 Mg km^{-2} across a savanna landscape in southern Africa. The variation in grass fuel load is attributed to differences in grass species and hence biomass distribution as observed in the field and modeled by Kidnie (2009), who predicted a linear relation between grass height and fuel load accumulation. The order of combusted herbaceous/grassy vegetation was grassland > savanna >woody savanna>shrubland at about 99/99%, 82/91%, 90/63% and 44/22%, respectively, of total combusted fuel in November/January. The relatively high amount of combusted herbaceous material in the early burn season is attributed to the relatively easy drying nature of the herbaceous materials (mostly grasses) that promote combustibility shortly after the onset of the dry season.

One will expect that combustibility of herbaceous materials will increase with time due to a drying effect, which should induce higher fuel load combustion by the late burn season. This is indeed the case: The higher early season combusted fuel load across savanna, woody savanna, and shrubland vegetation is attributed to substantial consumption of fuel load material during early burns that results in temporal reduction of herbaceous fuel load by the late season. Across grassland vegetation, however, components of other vegetation parts (leaves/twigs) are limited with ~0 Mg km^{-2} leaf cover by the late season; this results in ~99% herbaceous coverage. Because the vegetation cover is almost entirely herbaceous in nature, the temporal drying effect results in higher combustibility.

Combusted leaf fuel load

Contrary to combusted herbaceous plants, shrubland has the highest amount of combusted leaves at 114 Mg km^{-2} and 253 Mg km^{-2} in November and January burns, respectively, constituting 32% and 72% of total combusted fuel loads. The lowest combusted leave fuel load across grassland vegetation at 2.7 Mg km^{-2} and 0 Mg km^{-2} was anticipated, since the vegetation type has virtually no leaves during the dry season.

Ash remains and loss in mass

Mean total ash loads of 32±5 to 120±14 Mg km^{-2} during early burns and 48±4 to 90±4 Mg km^{-2} during late burns are comparable to the values 45±3 to 134±2 Mg km^{-2} obtained by Bagamsah (2005) across similar vegetation types in the study area.

The significantly low ash remains compared to the original fuel load before combustion (Table 4.6) is attributed to the combustion and loss of elements in particulate and non-particulate forms during burns. Ashes were darker in color, indicating a relatively incomplete combustion of original organic matter compared to inorganic wood ash (Ulery et al. 1993). The highest ash amounts collected across shrubland vegetation of 121 Mg km^{-2} and 89 Mg km^{-2} in November and January, respectively, might be attributed to comparatively high products of incomplete combustion in this vegetation type and the relatively high share of combusted twigs across the shrubland vegetation (Table 4.4).

The least ash was collected across grassland vegetation at 32 Mg km^{-2} and 56 Mg km^{-2} in November and January, respectively. Generally, the fine ash fraction was consistently greater than the coarse ash fraction suggesting a relatively complete combustion during the dry season. Across savanna, woody savanna and shrubland vegetation types, quantities of ash remains were higher for early burns than for late burns, while across grassland vegetation the quantity of late burn ash was higher than that of the early burn.

Table 4.6 t-test of statistical difference between fuel load nutrient distribution before combustion (Mg km^{-2}) and nutrient load in ash after combustion, and also between coarse ash nutrient concentration and fine ash nutrient concentration

	Mean	Std	Mean	Std	n	t	Sig. (2-tailed)
Fuel load and Ash load (Mg km^{-2})							
November							
	Fuel load		Ash				
Load	436	188	86	44	40	11.5	<0.001
N	6.6	3.6	0.3	0.16	40	11.3	<0.001
P	0.3	0.2	0.1	0.07	40	8.3	<0.001
K	1.1	0.5	0.5	0.2	40	7.0	<0.001
Ca	1.3	0.6	0.7	0.3	40	6.4	<0.001
Mg	0.4	0.2	0.3	0.14	40	5.6	<0.001
Na	0.2	0.08	0.04	0.02	40	8.1	<0.001
January							
Load	413	134	60	21	39	16.1	<0.001
N	3.7	1.5	0.2	0.1	39	15.2	<0.001
P	0.3	0.2	0.9	0.03	39	9.7	<0.001
K	1.1	0.4	0.5	0.2	39	9.4	<0.001
Ca	1.1	0.4	0.5	0.1	39	8.0	<0.001
Mg	0.4	0.2	0.2	0.1	39	7.1	<0.001
Na	0.1	0.06	0.04	0.02	39	7.1	<0.001
Difference between coarse ash and fine ash nutrient concentration (mg g^{-1})							
November							
	Coarse ash		Fine ash				
N	5.06	1.44	2.89	1.55	40	6.4	<0.001
P	1	0.25	2.58	3.09	40	-3.2	<0.001
K	4.13	1.7	8.15	2.71	40	-8.6	<0.001
Ca	5.15	1.19	10	2.5	40	-12.4	<0.001
Mg	1.78	0.57	3.9	1	40	-13.2	<0.001
Na	0.24	0.24	0.56	0.2	40	-7.7	<0.001
January							
N	5.47	1.47	1.99	0.77	39	11.7	<0.001
P	1.28	0.36	1.58	0.45	39	-4	<0.001
K	4.8	2.2	9.05	2.59	39	-11	<0.001
Ca	5.03	1.64	8.7	1.34	39	-10	<0.001
Mg	1.98	1.13	3.22	0.8	39	-5.8	<0.001
Na	0.33	0.37	0.72	0.16	39	-6.3	<0.001

Loss in mass due to combustion varied from 65% of combusted fuel load across shrubland vegetation to 93% across grassland vegetation. The loss in mass confirms losses in some components of the original content of vegetation before combustion (Dijkstra et al. 2010). Loss in mass due to combustion was in the order grassland>savanna>woody savanna>shrubland. This order suggests complete combustion in similar vegetation order across the study area.

4.3.3 Fuel load elemental concentrations before and after combustion

Plant tissue/ash C and N concentration; and C:N concentration ratios

Nitrogen and C concentrations varied across the various vegetation types and by plant part (Table 4.7). Perry and Hickman (2001) reported significant differences in leaf-N concentration of 25 tree species ranging from 10-36 mg g^{-1}. Hoffmann et al. (2005) estimated the N content of savanna leaf tissues to be 11.7-17.9 mg g^{-1}, which are similar to values (11-12.6) reported by Ratnam et al. (2008) across the savanna Kruger national park of southern Africa. The N concentrations of 12-21 mg g^{-1} in leaves, 9-20 mg g^{-1} in herbs and 11-17 mg g^{-1} in twigs are comparable and within range of tissue N content (Reuter and Robinson 1997; Perry and Hickman 2001; Hoffman et al. 2005; Ratnam et al. 2008) but generally higher than values (3.1-8.7 mg g^{-1} in leaves, 3.3-5 mg g^{-1} in grass and 3-6.6 mg g^{-1} in twigs) recorded by Bagamsah (2005) across the same area. Similarly, mean plant tissue C concentration of 370-460 mg g^{-1} in leaves, 420-460 mg g^{-1} in herbs and 370-470 mg g^{-1} in twigs are comparable to values of 400-440 mg g^{-1} recorded across southern African savannas by Craine et al. (2008) and 420-430 mg g^{-1} across similar African savanna landscapes by Ries and Shugart (2008).

The concentration of N in January was higher in leaves compared to twigs and herbs (Appendix 3). A similar observation for leaf C concentration compared to herbs and twigs for both November and January sampling (Appendix 3) could be due to the high chlorophyll-related photosynthetic functions of the leaves relative to the other plant parts (Imani and Rostamikia 2011).

Tissue-C concentrations are generally higher in January than November (Table 4.8), while tissue N concentrations are higher in November compared to January. This variations in seasonal N and C concentrations results in a higher C:N ratio in January compared to November. Given the relatively low late-season moisture content and enhanced spread of fire, the observed high January C concentration renders late burns more susceptible to emissions of C per unit fuel load burned.

Table 4.7 Carbon and nitrogen concentration and C:N ratio of different plant tissues before combustion and in ash after combustion of representative vegetation covers across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Carbon (mg g^{-1})										
Leaves	432^{a} (4)	459 (3)	420^{a} (16)	446 (3)	373 ^{b} (54)	NL	457^{a} (3)	456 (5)	0.010	0.089
Herbs	437^{b} (4)	455^{A} (3)	432^{ab} (5)	426^{B} (7)	443^{a} (6)	451^{A} (2.5)	421^{b} (5)	445^{A} (3)	0.025	<0.001
Twigs	372^{b} (17)	437^{B} (15)	393^{ab} (21)	440^{B} (4)	414^{ab} (40)	474^{A} (7)	447^{a} (8)	471^{A} (3)	0.037	0.001
Fine	76^{b} (6)	67 (4)	108^{a} (8)	92 (10)	79^{b} (8)	82 (5)	69^{b} (10)	100 (18)	0.012	0.179
Coarse	220 (37)	412 (19)	292 (33)	399 (40)	306 (23)	316 (30)	280 (61)	361 (17)	0.207	0.106
Nitrogen (mg g^{-1})										
Leaves	21.1^{ab} (1.3)	13.2 (0.5)	18.6^{ab} (1)	13 (0.9)	16.8^{b} (0.9)	NL	22.9^{a} (1)	12.4 (0.6)	0.035	0.717
Herbs	13.9^{b} (0.8)	7.5^{B} (0.5)	19.8^{a} (1.2)	8.6^{B} (0.5)	9.6^{c} (0.6)	7.5^{B} (0.7)	15.5^{b} (0.9)	10.8^{A} (0.6)	<0.001	0.001
Twigs	16.7^{a} (0.5)	11 (1.6)	12.8^{b} (1.3)	11.1 (1)	17.5^{a} (1.3)	13.4 (4.1)	17^{a} (1.4)	11.7 (1.1)	0.042	0.806
Fine	4^{a} (0.5)	2.0 (0.3)	1.5^{c} (0.2)	2.2 (0.3)	3.5^{ab} (0.3)	1.9 (0.2)	2.6^{bc} (0.5)	1.7 (0.2)	0.001	0.576
Coarse	4.5 (0.5)	5.9 (0.5)	4.7 (0.4)	4.7 (0.4)	5.9 (0.4)	5.6 (0.6)	5.1 (0.5)	5.6 (0.4)	0.158	0.265
C:N concentration ratio										
Leaves	21 (1)	35 (1)	23 (2)	36 (2)	22 (3)	NL	20 (1)	37 (2)	0.442	0.688
Herbs	32^{b} (4)	63^{AB} (4)	23^{c} (1)	51^{BC} (4)	48^{a} (3)	67^{A} (8)	28^{bc} (2)	43^{C} (3)	<0.001	0.010
Twigs	23^{b} (1)	46 (6)	33^{a} (4)	42 (3)	24^{b} (2)	41 (10)	28^{ab} (3)	45 (6)	0.042	0.953
Fine	24^{b} (5)	36 (3)	76^{a} (6)	54 (11)	26^{b} (5)	45 (4)	33^{b} (5)	59 (9)	<0.001	0.176
Coarse	53 (9)	69 (11)	66 (9)	91 (13)	53 (4)	62 (9)	61 (8)	67 (6)	0.575	0.183

Fine = fine ash, Coarse=coarse ash, Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling, NL = No leaf, hence not included in the analyses of variance test

Table 4:8 Pair wise t-test of statistical difference in fuel load/ash elemental concentrations between early (November) vegetation-burn and late (January) burn for different vegetation covers across the northern region of Ghana during the 2010-2011 fire season. n = 10, means and standard error of means provided in Tables 4.7, 4.9 and 4.10.

	Savanna		Woody savanna		Grassland		Shrubland	
	t	sig. level	t	sig. level	t	sig. level	t	sig. level
Carbon								
Leaf	-4.5	<0.001	-1.5	0.162	---	---	0.3	0.797
Herb	-3.1	0.010	0.8	0.435	-1.4	0.191	-3.7	0.007
Twig	-1.6	0.192	-1.9	0.114	-3.4	0.182	-3.1	0.013
Fine	1.4	0.214	1.0	0.343	-0.3	0.763	-1.4	0.191
Coarse	-4.0	<0.001	-2.2	0.063	-0.6	0.591	-3.4	0.008
Nitrogen								
Leaf	5.2	<0.001	4	<0.001	---	---	9.7	<0.001
Herb	6.4	<0.001	11.5	<0.001	1.9	0.092	4.1	0.004
Twig	2.9	0.051	1.7	0.142	0.1	0.955	2.3	0.043
Fine	3.4	0.013	-1.9	0.091	4.9	<0.001	1.6	0.152
Coarse	-2.1	0.071	0	0.999	0.3	0.771	-0.8	0.452
Phosphorus								
Leaf	-2.1	0.083	3.4	0.011	---	---	-0.8	0.446
Herb	-10.3	<0.001	2.8	0.023	-6.3	<0.001	1.5	0.171
Twig	-0.1	0.921	9.6	<0.001	-31	0.022	1.0	0.362
Fine	-1.3	0.234	0.2	0.821	2.7	0.021	0.4	0.674
Coarse	-5.2	<0.001	-1.0	0.336	-6.8	<0.001	-0.8	0.449
Potassium								
Leaf	3	0.022	-0.9	0.376	---	---	-6.3	<0.001
Herb	3.5	0.010	0.0	0.994	-3.0	0.014	-10.3	<0.001
Twig	0.8	0.492	-3.4	0.013	-0.2	0.861	-3.7	0.005
Fine	-3.8	<0.001	0.3	0.784	-1.4	0.193	1.4	0.193
Coarse	-0.7	0.532	-3.3	0.012	-0.9	0.375	-0.7	0.504
Calcium								
Leaf	4.3	<0.001	1.3	0.231	---	---	2.6	0.030
Herb	5.8	<0.001	-0.8	0.465	0.4	0.673	-1.1	0.316
Twig	-0.4	0.722	1.3	0.253	8.2	0.084	0.5	0.641
Fine	3.4	0.013	0.3	0.784	2.1	0.071	1.1	0.291
Coarse	3.2	0.011	4.3	<0.001	-1.3	0.235	-1.3	0.210
Magnesium								
Leaf	4.1	0.012	2.6	0.033	---	---	2.9	0.016
Herb	0.0	0.984	-0.9	0.391	-6.5	<0.001	2.2	0.056
Twig	2.3	0.083	1.0	0.365	-2.0	0.310	1.5	0.173
Fine	2.3	0.051	1.4	0.270	3.1	0.012	0.9	0.379
Coarse	2.6	0.031	1.4	0.195	-1.4	0.211	-1.6	0.149
Sodium								
Leaf	6.9	<0.001	2.1	0.061	---	---	2.2	0.054
Herb	2.8	0.023	1.1	0.293	1.3	0.221	-1.5	0.171
Twig	1.0	0.387	0.2	0.845	0.7	0.624	0.4	0.692
Fine	-1.2	0.289	-3.1	0.011	-0.9	0.393	-4.5	0.001
Coarse	0.2	0.831	-3.8	<0.001	-1.8	0.121	-0.6	0.557

Similar observation was recorded for fine ash and coarse ash C concentrations. The ash C and N concentrations are, however, higher than the mean values of 0.08 and 1.4 mg g^{-1}, respectively, reported by Raison and McGarity (1979) across savanna vegetation suggesting a relatively incomplete combustion during annual fires across the landscape. Carbon and N in plant tissues are usually observed to decline with increasing temperature. Qian et al. (2009) observed a consistent decline in concentration of C and N from before combustion at ~450 mg g^{-1} and ~16 mg g^{-1}, respectively, to close to ~0 mg g^{-1} with 600˚C. The comparatively high ash C and N concentration is attributed to some unburned plant tissues in the ash material.

The significant November fine ash C and N across the different vegetation types (Table 4.7) is attributed to the differences in combustibility of fuel load due to varying moisture contents.

Concentrations of C and N in plant tissues were consistently higher than in burned ash. With the comparatively low mass (Mg km^{-2}) of ash remains in relation to the mass of original plant fuel load (Table 4.6), and as recorded for the various vegetation types (Table 4.4), this observation confirms the volatilization of C and N into the atmosphere during combustion (Knights 1966; Norman and Wetselar 1960). Carbon and N loss is due to their relatively high volatilization temperature, resulting in a low ash C and N concentration and a comparatively high concentration of other non-volatile elements.

The C:N ratio of plant tissues that fall to the ground and of accumulating ash is very important in the conservation of the soil's N. November ash C:N ratio was generally higher than that of the November plant tissue. Carbon is required for energy building, while N is required for tissue building in plants and in decomposing bacterial and fungi. Miller (2000) established that a tissue C:N ratio > 33 results in the withdrawal of soil N due to excess use of available N and its incorporation into microbial tissues. A C:N ratio between 17 and 33 has no withdrawal effect while a C:N ratio less than 17 results in an increase in soil N. Kelly et al. (2011) and Ross et al. (2004) argued that a low C:N ratio promotes microbe-related nitrification processes of the soil with a net release of N into the soil system. Should plant litter fall to the ground and decompose then, compared to the accumulated ash, the high C:N of ash compared to the plant tissues will consequently reduce the availability of N on which decomposing fungi and bacterial depend for nutrition. Consequently, microbes will consume the soil N, creating a deficiency in the soil and reducing the temporal growth of plants.

Plant tissue/ash P and K concentration and N:P concentration ratio

The mean plant tissue P concentration of 0.45-1.1 mg g^{-1} (Table 4.9) falls within values reported in literature for various plants (Knox et al. 2011; Riginos 2009; Mandal et al. 2004; Tessier and Raynal 2003; Summer and Williams 2001; Shahla et al. 1988). For instance, Holdo (2003) estimated leaf P concentrations across a savanna shrubland in Zimbabwe to be 0.9-3 mg g^{-1}. Hoffmann et al. (2005) estimated the P concentrations of savanna leaves to be 0.5-0.8 mg g^{-1}, while Ratnam et al. (2008) estimated mean P concentration of senesce leaves across the savanna Kruger national park of south Africa to be 0.67-0.87 mg g^{-1} and the concentration of green leaves to be higher at 1.65-1.84 mg g^{-1}. Riginos (2009) quantified the P concentration of grasses at locations in Kenya to be 1.2-1.7 mg g^{-1}, while Craine et al. (2008) reported the P concentration of southern African grasses to be 0.6-2.8 mg g^{-1}. Wider grass species distribution across the different vegetation types and the availability of twigs from different parts of various plants explain the wider variations in mean plant tissue P concentration in herbaceous parts (0.56-1.03 mg g^{-1}) and twigs (0.51-1.1 mg g^{-1}) than in leaf tissues (0.57-0.81 mg g^{-1}) across the various vegetation types. Grasses/herbs are generally associated with relatively high P concentrations. Plant tissue P concentration was not significantly different (P = 0.708) between the vegetation parts (leaves, grasses/herbs, twigs) during November sampling but differed (P = 0.005) in January (Appendix 3).

The comparatively high grass P concentration in January compared to leaf and twig P is attributed to comparatively high grass adaptability to nutrient uptake in the dry season. Bond (2008) argued that the dense fibrous root systems of grasses tend to explore soil more intensively than trees, and in the process out-compete trees for nutrient supply in locations where they occur together. Walter (1971) proposed the niche differentiation hypothesis where he submits that tree cover across savanna landscapes may be predicted by the quantity of water and nutrients that percolates beyond the grass root zone to deeper soil horizons where trees have exclusive access.

Table 4.9 Concentration of phosphorus, potassium concentration and N:P ratio of different plant tissues before combustion and in ash after combustion of representative vegetation covers across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
					Phosphorus (mg g^{-1})					
Leaves	0.58^{b}	0.75^{A}	0.81^{a}	0.57^{B}	0.58^{b}	NL	0.71^{ab}	0.79^{A}	0.005	0.034
	(0.02)	(0.07)	(0.06)	(0.03)	(0.11)		(0.04)	(0.07)		
Herbs	0.63^{b}	0.85^{A}	1.03^{a}	0.91^{A}	0.59^{b}	0.93^{A}	0.69^{b}	0.56^{B}	<0.001	<0.001
	(0.01)	(0.03)	(0.05)	(0.03)	(0.03)	(0.04)	(0.04)	(0.05)		
Twigs	0.51^{c}	0.51^{C}	1.03^{a}	0.45^{C}	0.51^{c}	1.1^{A}	0.8^{b}	0.7^{AB}	<0.001	<0.001
	(0.02)	(0.08)	(0.06)	(0.04)	(0.01)	(0.09)	(0.06)	(0.03)		
Fine	1.44^{b}	1.66^{A}	1.7^{b}	1.62^{A}	5.98^{a}	1.9^{A}	1.24^{b}	1.17^{B}	<0.001	0.001
	(0.04)	(0.14)	(0.08)	(0.13)	(1.5)	(0.11)	(0.11)	(0.09)		
Coarse	0.85^{b}	1.13^{B}	1.34^{a}	1.47^{A}	0.89^{b}	1.48^{A}	0.95^{b}	1^{B}	<0.001	0.001
	(0.03)	(0.05)	(0.05)	(0.13)	(0.04)	(0.11)	(0.07)	(0.04)		
					N:P concentration ratio					
Leaves	36^{a}	19	25^{a}	23	30^{ab}	NL	33^{ab}	17	0.014	0.175
	(2)	(3)	(3)	(2)	(5.5)		(2)	(2)		
Herbs	22^{a}	9^{B}	20^{ab}	10^{B}	17b	6^{B}	23^{a}	20^{A}	0.038	<0.001
	(2)	(0.6)	(2)	(0.7)	(1.4)	(1)	(1.4)	(1)		
Twigs	34^{a}	25^{A}	13^{c}	26^{A}	34^{a}	12^{B}	23^{b}	16^{AB}	<0.001	0.038
	(2)	(6)	(1.5)	(3)	(2.3)	(3)	(3)	(2)		
Fine	2.7^{a}	1.3	1^{c}	1	1.4^{bc}	1	2^{ab}	1.6	0.001	0.283
	(0.4)	(0.2)	(0.1)	(0.3)	(0.4)	(0.1)	(0.4)	(0.2)		
Coarse	5.4^{a}	5.5^{A}	3.5^{b}	3.4^{B}	6.7^{a}	4^{B}	5.7^{a}	5.6^{A}	0.001	0.003
	(0.6)	(0.6)	(0.3)	(0.4)	(0.5)	(0.5)	(0.7)	(0.3)		
					Potassium (mg g^{-1})					
Leaves	2.4	1.7^{C}	2.1	2.3^{B}	1.9	NL	2.2	3.2^{A}	0.626	<0.001
	(0.2)	(0.1)	(0.2)	(0.1)	(0.5)		(0.1)	(0.1)		
Herbs	2.8^{a}	2.2^{C}	2.6^{a}	2.7^{B}	2b	2.7^{B}	2.5^{a}	4.1^{A}	0.001	<0.001
	(0.2)	(0.1)	(0.1)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)		
Twigs	1.3	0.8^{C}	1.3	2.2^{B}	1.6	2.1^{B}	1.7	3^{A}	0.734	0.000
	(0.3)	(0.1)	(0.1)	(0.2)	(0.4)	(0.04)	(0.3)	(0.2)		
Fine	8	10.4^{B}	8	7.8^{C}	9.5	11.8^{A}	7.2	6.2^{D}	0.310	<0.001
	(0.6)	(0.4)	(0.5)	(0.5)	(1.3)	(0.6)	(0.7)	(0.1)		
Coarse	4.7^{a}	4.9^{AB}	3.4^{b}	4.4^{B}	5.4^{a}	6.4^{A}	3.0^{b}	3.4^{B}	0.002	0.017
	(0.4)	(0.3)	(0.2)	(0.3)	(0.8)	(1.1)	(0.4)	(0.4)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling and capital superscripted letters for January sampling; NL = No leaf sampled, hence not included in the analyses of variance test.

Given the high iron-bearing sesquioxide contents of soils of the study area and their ability to bind P under the prevailing slightly acidic conditions (Owusu-Bennoah et al.

2000), mobility of P should decrease with depth as a result of which it might be restricted to the topsoils where grasses have formidable advantage in their extraction.

The relatively low leaf P concentration in January across woody savanna vegetation compared to November might be attributed to redeployment of P to other parts of the plants during the dry season (Wright and Westoby 2003). Besides grass P concentration, lower N and P concentrations of leaf and twig tissues towards the end of the dry season (January) compared to the concentrations at the beginning of the dry season (November) also suggests that N and P might be resorbed through the plant's own seasonal nutrient controlling mechanism into the plant system, and hence are tightly conserved by trees in this savanna system. Aerts and Vanderpeijl (1993), Aerts (1999), Kobe et al. (2005) give an in-depth reasoning to the principle of nutrient resorption under unfavorable nutrient uptake conditions: A nutrient-controlling mechanism, which plays essential roles in low-nutrient environments where even small nutrient losses can have significant negative impacts on plant survival and which defines the competitive ability of plant survival and fitness to grow under changing seasonal conditions. Gusewell and Koerselman (2002) and Gusewell (2005) argue that the extent to which a particular nutrient is resorbed by plants is not only determined by the peripheral tissue concentration difference but also by its relative availability for plant uptake compared to other nutrients. This argument and observed seasonal variation suggests P limitation in soils across the region, and presupposes that most P in leaves and twigs that eventually burn are redeployed to the plant's system, conserved and are not readily combusted and lost during burns.

In January, the relatively dry conditions also constrain nutrient mobility and availability for plant root uptake (Schimel and Parton 1986). The relative decline in dry-season tissue N and P across woody savanna vegetation confirms observations by Ratnam et al. (2008) who observed a decline in N and P concentrations of senesce leaves of fine-leaved and coarse-leaved trees, and who also attributed the decline in concentration to nutrient conservation by plants in other savanna systems across southern Africa.

November grass P concentrations were generally lower than in January, t (40) =-2.1, P = 0.045. Values were higher in the early than in the late burn season across the woody savanna vegetation (Table 4.8). The higher January values for herbaceous plants than those in November across savanna and grassland vegetation could not be readily explained, but might be attributed to a comparatively efficient nutrient uptake by the fibrous root system under water stress conditions and a relatively low late season energy usage.

Mean N:P concentration ratios varied across the various vegetation types in both months and ranged from 17-36 in leaves, 6-22 in grass/herbaceous plants and 12-34 in twigs. These values are comparable to those reported in literature for various plants (Boyer and Wheeler 1989; Jacobson and Pettersson 2001) and across the West African grasslands (Craine et al. 2008; Penning de Vries et al.1980). The N:P concentration ratios of plant parts are in the order leaves > twigs > herbs (Appendix 3). The N:P ratios of leaves across the various vegetation types did not vary much compared to those of twigs and herbs. Tessier and Raynal (2003) reported extensively on N: P concentration ratios of numerous plants and how the ratio reflects soil N and P limitations. Mostly, they estimtated N:P ratios less than 14 to indicate limitations in soil N while ratios greater than 16 indicate soil P limitation. Penning de Vries et al. (1980), however, estimated N:P ratios of less than 7 to imply N limitation and ratios greater than 26 to imply P limitation across West African grasslands. General plant growth across the northern region of Ghana, inferred from the N:P concentration ratios, indicates soil P limitation across the region.

Mean fuel load potassium concentrations of 1.7-3.2 mg g^{-1} in leaves, 2-4.1 mg g^{-1} in grasses and 0.8-3 mg g^{-1} in twigs were slightly lower than anticipated across the study area but generally comparable to those in literature for various plants (Tefera et al. 2008) and also comparable to values of 1.3-3.3 mg g^{-1} (leaves), 1.6-3 mg g^{-1} (grass) and 0.9-2.3 mg g^{-1} (twigs) recorded by Bagamasah (2005) across same area. In other African savanna systems, Hoffmann et al. (2005) estimated tree-leaf K concentrations to be higher at 4.2-7.2 mg g^{-1}, while grass K concentrations were estimated to be 2-20 mg g^{-1} across the Kruger national park by Mutunga et al. (2004). The K concentration by plant parts was generally in the order herbs> leaves> twigs (Appendix 3).

Except in the fine ash collected in November, which did not show any differences in P and K concentrations across the various vegetation types, the concentration of P and K in ash varied across vegetation types in both months. Misra et al. (1993) estimated P and K concentrations of ash at 600˚C for various plant tissues, and found P to be in the range of 0.8-15.6 mg g^{-1} and ash K concentration to range from 9.7-162 mg g^{-1}. The estimated ash P and K concentrations are within range of values reported by Misra et al. (1993). The significantly high fine ash P and K concentrations compared to those in the coarse ash (Table 4.6, Table 4.9) were anticipated and attributed to a high degree of burn in the fine ash, which let to higher C and N losses resulting in a more concentrated P and K in the burned matter. Consequently, ash P and K concentrations are higher than the respective concentrations in plant tissues before combustion. This also explains the low ash N:P ratios observed across the various vegetation types. Early-season fine ash P concentration was higher than late-season across grassland vegetation. For coarse ash however, the late-season P concentration was higher than the early season concentrations across all vegetation types (Table 4.8).

Plant tissue and ash Ca, Mg and Na concentrations

Fuel load Ca, Mg and Na concentrations varied across the vegetation types (Table 4.10). Mean Ca concentration ranged from 2.8-3.5 mg g^{-1} in leaves, 2.6-3.4 mg g^{-1} in grass and 2.5-2.9 mg g^{-1} in twigs. Holdo (2003) estimated leaf Ca concentration of a Zimbabwen bushland and tree savanna to be 0.7-17.1 mg g^{-1}, while Hoffmann et al. (2005) estimated it to be 4.3-6.7 mg g^{-1}. A grass Ca concentration of 1.7-3.9 mg g^{-1} was reported by Stowe and Bonyongo (2003) across Botswana, while Mutunga et al. (2004) reported values of 1-9 mg g^{-1} across other African savanna systems. The mean Mg concentration ranging from 0.1-1.5 mg g^{-1} in leaves, 0.4-1.5 mg g^{-1} in grass, and 0.34-1.8 mg g^{-1} in twigs is comparable to literature values of 1-5 mg g^{-1} estimated by Mutunga et al. (2004) across grasslands in Africa and 2.1-2.6 mg g^{-1} estimated across other savanna systems (Distel et al. 2005). The mean Na concentration range of 0.16-0.33 mg g^{-1} in leaves, 0.28-0.45 mg g^{-1} in grass and 0.1-0.31 mg g^{-1} in twigs is comparable to values reported in literature (Bagamsah 2005; Distel et al. 2005; Hoffmann et al. 2005; Mutunga et al. 2004).

As with P and K ash concentrations, the concentration of Ca, Mg and Na in fine ash were higher than in coarse ash (Table 4.6). Ca, Mg and Na concentrations in ash were higher in fine and coarse ash than in plant tissues prior to burning (Table 4.10) due to volatilization losses of C and N during combustion. Similar plant tissue concentrations were recorded by Bagamsah (2005), Bowell and Ansah (1994) across the study area.

Table 4.10 Calcium, magnesium and sodium concentration in different plant tissues before combustion and in ash after combustion of representative vegetation covers across the northern region of Ghana in November 2010 and January 2011.Values are means, with standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Calcium (mg g^{-1})										
Leaves	3.5	2.8^{AB}	3.2	3.1^{A}	2.7	NL	3.2	2.3^{B}	0.294	0.009
	(0.1)	(0.1)	(0.2)	(0.1)	(0.2)		(0.2)	(0.2)		
Herbs	3.4^{a}	2.6^{B}	2.9^{b}	3.1^{A}	2.8^{b}	2.7^{AB}	2.9^{b}	3.2^{A}	0.014	0.033
	(0.1)	(0.1)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.2)		
Twigs	2.6	2.5	2.6	2.5	2.9	2.6	2.6	2.5	0.805	0.976
	(0.2)	(0.2)	(0.1)	(0.1)	(0.2)	(0.2)	(0.3)	(0.1)		
Fine	12^{a}	9.1^{AB}	8.6^{b}	8.4^{AB}	11.2^{a}	9.3^{A}	8.6^{b}	7.9^{B}	0.001	0.040
	(0.9)	(0.3)	(0.3)	(0.5)	(0.6)	(0.5)	(0.7)	(0.2)		
Coarse	5.1	3.9^{B}	4.6	3.9^{B}	5.8	6.5^{A}	5.1	5.7^{A}	0.155	<0.001
	(0.2)	(0.4)	(0.2)	(0.1)	(0.5)	(0.7)	(0.4)	(0.2)		
Magnesium (mg g^{-1})										
Leaves	1.5^{a}	1.0	1.2^{a}	1.1	0.1^{b}	NL	1.4^{a}	0.8	<0.001	0.152
	(0.1)	(0.1)	(0.1)	(0.1)	(0)		(0.1)	(0.1)		
Herbs	1.1^{b}	1.1	1.1^{b}	1.2	0.4^{c}	1.0	1.5^{a}	1.2	<0.001	0.220
	(0.1)	(0.1)	(0.1)	(0.1)	(0.02)	(0.1)	(0.1)	(0.1)		
Twigs	1.8^{a}	0.9	1^{b}	1.0	0.3^{c}	0.8	1.2^{b}	1.0	<0.001	0.570
	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)	(0.1)	(0.1)		
Fine	4.7^{a}	3.7^{A}	3.1^{b}	2.8^{B}	4.4^{a}	3.4^{AB}	3.5^{b}	3.1^{AB}	<0.001	0.040
	(0.3)	(0.3)	(0.2)	(0.1)	(0.2)	(0.2)	(0.3)	(0.3)		
Coarse	1.9	1.6^{BC}	1.4	1.2^{C}	2	2.3^{AB}	1.9	2.8^{A}	0.131	0.003
	(0.1)	(0.2)	(0.1)	(0.1)	(0.3)	(0.3)	(0.2)	(0.5)		
Sodium (mg g^{-1})										
Leaves	0.32	0.16^{B}	0.33	0.25^{A}	0.33	NL	0.28	0.2^{AB}	0.758	0.024
	(0.03)	(0.02)	(0.04)	(0.02)	(0.09)		(0.03)	(0.02)		
Herbs	0.45^{a}	0.28	0.33^{ab}	0.28	0.36^{ab}	0.3	0.31^{b}	0.38	0.043	0.171
	(0.05)	(0.03)	(0.04)	(0.03)	(0.04)	(0.03)	(0.02)	(0.05)		
Twigs	0.22	0.1	0.23	0.24	0.31	0.23	0.25	0.23	0.786	0.117
	(0.06)	(0.02)	(0.02)	(0.04)	(0.1)	(0.02)	(0.05)	(0.03)		
Fine	0.62	0.72	0.46	0.62	0.63	0.75	0.54	0.78	0.183	0.160
	(0.05)	(0.04)	(0.05)	(0.07)	(0.09)	(0.05)	(0.04)	(0.03)		
Coarse	0.27^{ab}	0.23^{B}	0.12^{b}	0.19^{B}	0.43^{a}	0.78^{A}	0.12^{b}	0.13^{B}	0.004	<0.001
	(0.05)	(0.05)	(0.01)	(0.02)	(0.12)	(0.16)	(0.01)	(0.01)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling, NL = No leaf sampled, hence not included in the analyses of variance test.

The ash Na concentrations are comparable to values of 0.6-0.8 mg g^{-1} obtained by Misra et al. (1993). The ash K and Ca concentrations, however, are generally lower than the 9.7-162 mg g^{-1} and 211-365 mg g^{-1} estimated by Misra et al. (1993), probably due to the relatively incomplete combustion associated with the field burns.

In November, Na concentrations were higher in herbs than in leaves and twigs (Appendix 3). The higher Ca concentrations in leaves compared to twigs and grass is attributed to the high transpiration (Gilliham et al. 2011) characteristics of leaves compared to the other plant parts. Higher contents of P, K, Ca, Mg and Na in grasses than in leaves and twigs is attributed to better adaptation of grass to the hot, dry stress conditions (King 2011).

4.3.4 Fuel load/ash elemental distribution and elemental losses during fires

Table 4.11 to Table 4.17 show the carbon (Mg km^{-2}) and plant nutrient/element distribution (kg km^{-2}) in the combusted fuel load before burn, the nutrient distributions in ash after combustion, and the subsequent losses in plant nutrients due to combustion across the various vegetation types during the November and January burns. Values estimated for December and February by Bagamsah (2005) are provided in Table 3.18 for comparison. Table 4.6 gives the corresponding t-test of significant differences between the nutrient load in plant tissue before combustion and the nutrient load in ash after combustion. Total combusted carbon load varied across the various vegetation types from 154-215 Mg km^{-2} in November to 142-248 Mg km^{-2} in January (Table 4.11). Grassland and savanna vegetation had the highest combusted carbon per unit area due to the high share of herbaceous plants. Carbon load in ash after combustion was lower than the original fuel load carbon before combustion (Table 4.6). Loss of carbon due to combustion was highest in grassland vegetation and savanna vegetations. A carbon loss of about 140-244 Mg km^{-2} is estimated to be lost to the atmosphere during November and January burns across the region.

The bulk of the combusted carbon load is from the grass/herbaceous component of the fuel load (Table 4.11), contributing 83-92%, 62-90% and 98-99% of the total combusted carbon across savanna vegetation, woody savanna and grassland vegetation, respectively (which together constitutes 97% of the total burned area across the northern region, Figure 3.2).

Table 4.11 Carbon load of plant tissues before combustion, carbon load in ash after combustion and gross loss of carbon due to bush fires in representative vegetation covers across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Carbon load before combustion (Mg km^{-2})										
Leaves	22^{b}	8^{BC}	13.5^{b}	29^{B}	0.9^{b}	0^{C}	52^{a}	115^{A}	0.001	<0.001
	(14)	(2.5)	(3.5)	(3.7)	(0.6)		(8)	(18)		
Herbs	179^{a}	176^{B}	161^{a}	88^{C}	209^{a}	245^{A}	65^{b}	28^{D}	0.001	<0.001
	(20)	(16)	(29)	(11)	(26)	(20)	(15)	(8)		
Twigs	15^{b}	8^{B}	3.8^{c}	25^{A}	1^{c}	3.6^{B}	38^{a}	10.5^{AB}	<0.001	0.041
	(3)	(4)	(1)	(10)	(0.4)	(2.4)	(5)	(2)		
Total	215	192^{B}	178	142^{C}	211	248^{A}	155	153^{BC}	0.287	<0.001
	(28)	(15)	(30)	(11)	(26)	(20)	(16)	(15)		
Carbon load in ash after combustion (Mg km^{-2})										
Fine	6^{a}	3^{B}	7^{a}	3.5^{B}	2^{b}	4^{B}	5.6^{a}	6.5^{A}	<0.001	0.002
	(0.4)	(0.3)	(0.9)	(0.3)	(0.3)	(0.5)	(0.6)	(1.1)		
Coarse	5b	1^{B}	10^{a}	4^{B}	1.5^{b}	3^{B}	9.3^{a}	8.3^{A}	0.001	0.001
	(1)	(0.4)	(2.3)	(1.3)	(0.3)	(0.8)	(1.7)	(1.8)		
Total	11^{b}	4^{B}	17^{a}	7.5^{B}	3.5^{c}	7^{B}	15^{ab}	14.8^{A}	<0.001	<0.001
	(1)	(1)	(3)	(1)	(1)	(1)	(2)	(2)		
Loss of carbon during combustion										
Mg km^{-2}	205	188^{B}	162	134^{C}	208	242^{A}	140	138^{C}	0.161	<0.001
	(27)	(15)	(29)	(11)	(26)	(19.6)	(16)	(15)		
%	94^{a}	98^{A}	88^{b}	94^{B}	98^{a}	97^{AB}	89^{b}	90^{C}	0.002	<0.001
	(0.4)	(0.3)	(3)	(1)	(0.3)	(0.5)	(2)	(2)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

Leaves are the second largest source of combusted carbon, with a higher November leaf carbon load across savanna and grassland vegetation than in January. The comparatively higher January load across woody savanna and shrubland vegetation is attributed to leaf senesces at this time of the year compared to November, leading to accumulation of a high leaf fuel load from 33-65 Mg km^{-2} across woody savanna vegetation and from 114-253 Mg km^{-2} across shrubland vegetation (Table 4.4). The observed higher January C concentration (section 4.3.3) also contributed to the increase in combusted leaf fuel carbon load. Twigs are associated with the lowest combusted carbon load (also see Appendix 2). This observation indicates that carbon storage in woody parts of plants (twigs and trees) is an efficient carbon sequestration means, since the twigs are less combusted, hence with lower emissions during burns across the savanna landscape.

For N, P and K where the respective volatilization temperatures were exceeded during burn (section 4.3.1), the total N load across grassland vegetation of 4459 kg km^{-2} and 4250 kg km^{-2} are comparably lower than the values of 3056 kg km^{-2} obtainted by Rossiter-Rachor et al. (2008) across a cover of invasive *Andropogon gayanus* in Australia. The combusted total P load across grassland vegetation (kg km^{-2}) of 208 and 508 in November and December is comparable to values of 439 and 600 estimated in December and January by Bagamsah (2005) across the same area.

Table 4.12 Nitrogen load of plant tissues before combustion, and in ash after combustion, and gross loss of nitrogen due to bush fires in representative vegetation covers across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Nitrogen load before combustion (kg km^{-2})										
Leaves	824^{b}	240^{BC}	622^{b}	851^{B}	44.5^{b}	0^{C}	2574^{a}	3142^{A}	<0.001	<0.001
	(454)	(78)	(178)	(155)	(31)	(0)	(411)	(499)		
Herbs	5713^{ab}	2942^{B}	7591^{a}	1639^{B}	4369^{bc}	4155^{A}	2455^{c}	803^{B}	0.004	<0.001
	(792)	(373)	(1533)	(223)	(397)	(573)	(629)	(181)		
Twigs	680^{b}	245	126^{c}	583	45^{c}	103	1341^{a}	263	<0.001	0.098
	(133)	(118)	(43)	(229)	(20)	(65)	(143)	(51)		
Total	7222^{a}	3378	8339^{a}	2909	4459^{b}	4258	6371^{ab}	4208	0.024	0.167
	(1221)	(369)	(1566)	(361)	(390)	(564)	(688)	(385)		
Nitrogen load in ash after combustion (kg km^{-2})										
Fine	307^{a}	91	90^{b}	86	94^{b}	91	225^{a}	117	<0.001	0.378
	(40)	(13)	(16)	(15)	(14)	(12)	(46)	(13)		
Coarse	86^{bc}	15^{B}	149^{ab}	50^{B}	29^{c}	45^{B}	170^{a}	124^{A}	<0.001	<0.001
	(12)	(5)	(23)	(15)	(7)	(6)	(35)	(24)		
Total	393^{a}	110^{B}	239^{b}	136^{B}	123^{b}	137^{B}	395^{a}	241^{A}	<0.001	<0.001
	(39)	(16)	(32)	(20)	(20)	(15)	(57)	(22)		
Loss of nitrogen during combustion										
kg km^{-2}	6828	3197	8101	2773	4336	4122	5976	3967	0.106	0.117
	(1211)	(364)	(1555)	(419)	(384)	(566)	(722)	(377)		
%	94^{b}	95	96^{a}	94	97^{a}	96	93^{b}	94	0.018	0.089
	(0.9)	(0.5)	(0.9)	(1.5)	(0.4)	(0.7)	(1.7)	(0.6)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

The estimated P distribution was, however, lower than the mean P load of 112 kg km^{-2} estimated by Rossiter-Rachor et al. (2008).

The total combusted K load (kg km^{-2}) across grassland vegetations of 970 to 1460 are comparable to mean K load of 1412 (Rossiter-Rachor et al. (2008). The total grassland K loads are also comparable to mean values of 1017 and 570 respectively determined for December and February across the study area by Bagamsah (2005).

Table 4.13 Phosphorus load in plant tissues before combustion and in ash after combustion, and gross loss of phosphorus due to bush fires in different vegetation covers across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Phosphorus load before combustion (kg km^{-2})										
Leaves	27^{b}	14^{B}	25^{b}	32^{B}	2^{b}	0^{B}	82^{a}	194^{A}	<0.001	<0.001
	(17)	(5)	(6)	(6)	(1)	(0)	(13)	(38)		
Herbs	256^{a}	329^{B}	373^{a}	180^{C}	282^{a}	499^{A}	110^{b}	40^{D}	0.002	<0.001
	(30)	(31)	(65)	(28)	(42)	(40)	(28)	(9)		
Twigs	21^{b}	14	10^{b}	20	1^{b}	9	69^{a}	16	<0.001	0.385
	(4)	(7)	(2)	(10)	(0.6)	(6)	(13)	(3)		
Total	304	354^{B}	408	232^{B}	285	508^{A}	261	250^{B}	0.081	<0.001
	(37)	(28)	(66)	(21)	(42)	(41)	(33)	(34)		
Phosphorus load in ash after combustion (kg km^{-2})										
Fine	118	74^{AB}	96	60^{B}	152	91^{A}	105	79^{AB}	0.363	0.045
	(12)	(8)	(12)	(7)	(42)	(9)	(11)	(10)		
Coarse	16^{c}	3.4^{B}	43^{a}	14^{AB}	4^{d}	14^{AB}	29^{b}	22^{A}	<0.001	0.014
	(2)	(2)	(6)	(4)	(1)	(4)	(3)	(5)		
Total	134	78	139	74	156	105	134	102	0.920	0.057
	(12)	(10)	(17)	(8)	(42)	(12)	(11)	(9)		
Loss of phosphorus during combustion										
kg km^{-2}	170^{ab}	261^{B}	269^{a}	158^{C}	129^{b}	402^{A}	127^{b}	148^{C}	0.046	<0.001
	(34)	(26)	(78)	(34)	(25)	(46)	(31)	(35)		
%	51	76	58	67	51	77	42	54	0.509	0.235
	(5)	(3)	(6)	(5)	(9)	(3)	(8)	(5)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

Except total fuel load P, K, and Ca distribution in November; and twig P, K, Ca distribution in January, which did not significantly differ across the various vegetation types, N, P, K, Ca, Mg and Na distribution in leaves, grass/herbs, twigs, and their total distribution significantly differed from one vegetation type to the other. Total combusted N was in the order woody savanna > savanna > shrubland > grassland for November burns and grassland > shrubland > savanna > woody savanna for January burns. Total combusted P was in the order woody savanna > savanna > grassland > shrubland during November burns and grassland > savanna > shrubland > woody savanna during January burns. Across woody savanna and shrubland vegetation, early fire-season fuel load P was higher than that of the late season due to the high combustible fuel load availability. Across savanna and grassland vegetation, however, early burns are associated with comparatively lower fuel load P combustion per unit burn area. Most P nutrients were combusted from the herbaceous component across the various vegetation types followed by leaves and twigs (Table 13, Appendix 2). Total combusted K was in the order savanna > woody savanna > grassland > shrubland for November burns, and grassland > shrubland > savanna > woody savanna for January.

Table 4.14 Potassium load in plant tissues before combustion and in ash after combustion, and gross loss of potassium due to bush fires in different vegetation covers across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Potassium load before combustion (kg km^{-2})										
Leaves	114^{b}	30^{B}	67^{b}	131^{B}	6^{c}	0^{B}	252^{a}	845^{A}	0.001	<0.001
	(65)	(9)	(18)	(19)	(4)	(0)	(45)	(151)		
Herbs	1130^{a}	840^{B}	980^{a}	490^{C}	960^{a}	1440^{A}	385^{b}	310^{C}	0.003	<0.001
	(147)	(89)	(173)	(58)	(140)	(104)	(87)	(67)		
Twigs	55^{b}	17	12^{b}	103	4^{b}	16	140^{a}	66	<0.001	0.071
	(21)	(8)	(3)	(58)	(2)	(10)	(33)	(11)		
Total	1300	885^{B}	1060	730^{B}	970	1460^{A}	780	1220^{A}	0.067	<0.001
	(170)	(94)	(177)	(71)	(140)	(107)	(77)	(105)		
Potassium load in ash after combustion (kg km^{-2})										
Fine	620^{a}	460^{AB}	480^{a}	310^{C}	230^{b}	560^{A}	603^{a}	410^{BC}	<0.001	0.001
	(56)	(32)	(64)	(34)	(29)	(60)	(64)	(25)		
Coarse	89^{a}	15^{B}	108^{a}	43^{AB}	21^{b}	70^{A}	93^{a}	69^{A}	<0.001	0.048
	(11)	(6)	(15)	(10)	(4)	(25)	(13)	(8.5)		
Total	710^{a}	477^{B}	590^{b}	350^{B}	250^{c}	630^{A}	696^{a}	480^{B}	<0.001	0.001
	(56)	(37)	(81)	(38)	(27)	(67)	(66)	(25)		
Loss of potassium during combustion										
kg km^{-2}	580^{a}	410^{B}	470^{ab}	370^{B}	715^{a}	830^{A}	80^{b}	740^{A}	0.037	0.013
	(160)	(88)	(170)	(106)	(156)	(133)	(110)	(113)		
%	44^{b}	42	43^{b}	53	68^{a}	54	10^{b}	58	0.022	0.469
	(11)	(8)	(19)	(7)	(6)	(7)	(9)	(4.5)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences (P ≤ 0.05) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

The high combustion of K, Ca and Mg across grassland in January is attributed to the high late-season combustible dry matter across the grassland vegetation (Table 4.4). In contrast, the comparatively higher combusted fuel load N, P, K, Ca, Mg and Na in November than in January across other vegetation types is attributed to the high fuel load accumulation in November across these vegetation types.

Table 4.15 Calcium load in plant tissues before combustion and in ash after combustion, and gross loss of calcium due to bush fires in different vegetation covers across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Calcium load before combustion (kg km^{-2})										
Leaves	170^{b}	50^{B}	100^{b}	170^{B}	7^{b}	0^{B}	360^{a}	620^{A}	0.003	<0.001
	(100)	(15)	(30)	(20)	(5)	(0)	(60)	(140)		
Herbs	1380^{a}	1000^{B}	1030^{a}	570^{C}	1350^{a}	1500^{A}	460^{b}	240^{D}	0.001	<0.001
	(170)	(80)	(180)	(90)	(190)	(155)	(109)	(56)		
Twigs	100^{b}	48^{AB}	23^{c}	140^{A}	7^{c}	19^{B}	210^{a}	57^{AB}	<0.001	0.049
	(23)	(20)	(6)	(55)	(3)	(13)	(35)	(10)		
Total	1650	1100^{B}	1150	880^{B}	1360	1520^{A}	1030	920^{B}	0.067	0.002
	(220)	(75)	(190)	(100)	(190)	(160)	(100)	(110)		
Calcium load in ash after combustion (kg km^{-2})										
Fine	960^{a}	402^{BC}	495^{b}	330^{C}	296^{b}	433^{B}	750^{a}	527^{A}	<0.001	<0.001
	(100)	(25)	(60)	(30)	(40)	(30)	(97)	(36)		
Coarse	100^{b}	14^{C}	150^{ab}	38^{BC}	27^{c}	63^{B}	160^{a}	124^{A}	<0.001	<0.001
	(10)	(4)	(20)	(8)	(5)	(16)	(28)	(20)		
Total	1060^{a}	417^{BC}	650^{b}	370^{C}	320^{c}	495^{B}	910^{ab}	650^{A}	<0.001	<0.001
	(90)	(30)	(80)	(30)	(40)	(30)	(80)	(31)		
Loss of calcium during combustion										
kg km^{-2}	590^{ab}	680^{B}	500^{ab}	510^{B}	1040^{a}	1030^{A}	120^{b}	270^{B}	0.001	0.002
	(230)	(60)	(150)	(130)	(170)	(174)	(152)	(109)		
%	36^{b}	60^{A}	44^{b}	59^{A}	76^{a}	67^{A}	11^{b}	29^{B}	<0.001	0.043
	(8)	(3)	(7)	(6)	(3)	(4)	(6)	(6)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

Most nutrients are combusted from the grass/herbaceous component across the various vegetation types followed by leaves. The January leaf nutrient distribution of 0 kg km^{-2} across grassland vegetation is due to the absence of leaves across this vegetation type in January. Less N is combusted from the twig components of the various vegetation types. Except November total P in ash, which was not significantly different between vegetation types, total ash N, P, K, Ca, Mg and Na significantly varied across the various vegetation types both in November and January. Total ash nutrients were significantly lower (P < 0.001) than combusted nutrients in fuel loads before combustion (Table 4.6).

Table 4.16 Magnesium load in plant tissues before combustion and in ash after combustion, and gross loss of magnesium in representative vegetation cover types across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets.

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Magnesium load before combustion (kg km^{-2})										
Leaves	62^{b}	17^{A}	36^{b}	65^{B}	0.3^{b}	0^{B}	154^{a}	226^{A}	<0.001	<0.001
	(30)	(6)	(9)	(10)	(0.2)	(0)	(20)	(60)		
Herbs	434^{a}	420^{A}	396^{a}	230^{B}	188^{b}	565^{A}	218^{b}	92^{C}	0.002	<0.001
	(65)	(60)	(70)	(40)	(20)	(70)	(40)	(20)		
Twigs	75^{a}	22^{AB}	9^{b}	55^{A}	0.8^{b}	5^{B}	93^{a}	23^{AB}	<0.001	0.034
	(20)	(10)	(2)	(20)	(0.4)	(3)	(15)	(5)		
Total	570^{a}	460^{AB}	440^{a}	350^{B}	190^{b}	570^{A}	465^{a}	340^{B}	<0.001	0.042
	(70)	(70)	(70)	(50)	(20)	(70)	(36)	(50)		
Magnesium load in ash after combustion (kg km^{-2})										
Fine	374^{a}	167^{A}	178^{c}	109^{B}	120^{c}	157^{AB}	292^{b}	204^{A}	<0.001	0.005
	(30)	(20)	(30)	(10)	(15)	(13)	(20)	(20)		
Coarse	36^{b}	4^{C}	47^{ab}	11^{BC}	10^{c}	23^{B}	60^{a}	58^{A}	<0.001	<0.001
	(5)	(2)	(7)	(2)	(1.5)	(6)	(10)	(9)		
Total	410^{a}	170^{BC}	225^{b}	120^{C}	130^{c}	180^{B}	350^{a}	260^{A}	<0.001	<0.001
	(30)	(20)	(30)	(7)	(15)	(15)	(30)	(20)		
Loss of magnesium during combustion										
kg km^{-2}	160	290^{AB}	215	230^{AB}	60	390^{A}	110	80^{B}	0.140	0.008
	(70)	(60)	(50)	(50)	(15)	(75)	(37)	(50)		
%	28	59^{A}	47	68^{A}	32	68^{A}	24	23^{B}	0.197	0.045
	(9)	(5)	(6)	(4)	(7)	(5)	(6)	(8)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance level. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

Rossiter-Rachor et al. (2008) estimated fire-induced elemental N, P, K, Ca and Mg losses (kg km^{-2}) across native Autralian grasses to be less (N: 1878, P: 50, K: 461, Ca: 1084, Mg: 622) than the corresponding losses for invasive species of the African grass *Andropogon gayanus* with losses of 2527 N, 59 P, 561 K, 1802 Ca and 1380 Mg. The estimated N and P losses across grasslands are higher than the values estimated by Rossiter-Rachor et al. (2008). While K loss values are comparable to values of Rossiter-Rachor et al. (2008), the Ca and Mg losses estimated in this study are lower than values estimated by Rossiter-Rachor et al. (2008). The estimated P, K, and Na losses (kg km^{-2}) are, however, comparable to values estimated by Bagamsah (2005) across the study area (Table 4.18) while the Ca and Mg losses are lower than those.

Table 4.17 Sodium load in plant tissues before combustion and in ash after combustion, and gross loss of sodium in representative vegetation cover types across the northern region of Ghana in November 2010 and January 2011. Values are means, standard error of mean in brackets

	Savanna		Woody savanna		Grassland savanna		Shrubland savanna		Sig. level	
	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan	Nov	Jan
Sodium load before combustion ($kg\ km^{-2}$)										
Leaves	13^{b}	3^{B}	10^{b}	15^{B}	1^{b}	0^{B}	32^{a}	52^{A}	0.001	<0.001
	(7)	(0.8)	(3)	(3)	(0.7)	(0)	(7)	(12)		
Herbs	181^{a}	112^{B}	116^{ab}	49^{C}	169^{a}	162^{A}	50^{b}	30^{C}	0.002	<0.001
	(30)	(17)	(24)	(6)	(30)	(24)	(13)	(10)		
Twigs	10^{b}	3^{B}	2^{b}	8^{A}	1^{b}	2^{B}	21^{a}	5^{AB}	0.002	0.041
	(4)	(2)	(0.5)	(2)	(0.3)	(1)	(7)	(1)		
Total	204	117^{AB}	129	72^{B}	171	164^{A}	103	87^{B}	0.052	0.003
	(30)	(20)	(25)	(5)	(30)	(24)	(15)	(10)		
Sodium load in ash after combustion ($kg\ km^{-2}$)										
Fine	49^{a}	33^{B}	29^{b}	25^{B}	15^{c}	36^{B}	47^{a}	52^{A}	<0.001	<0.001
	(5)	(4)	(4)	(3.7)	(2)	(4)	(6)	(4)		
Coarse	5^{a}	1^{B}	4^{a}	2^{B}	2^{b}	8^{A}	4^{a}	3^{B}	0.009	0.003
	(1)	(0.2)	(0.5)	(0.3)	(0.4)	(3)	(0.7)	(0.4)		
Total	54^{a}	33^{B}	32^{b}	27^{C}	17^{b}	43^{AB}	51^{a}	55^{A}	<0.001	<0.001
	(5)	(4)	(5)	(3)	(2)	(4)	(6)	(4)		
Loss of sodium during combustion										
$kg\ km^{-2}$	150^{a}	84^{AB}	97^{ab}	45^{B}	154^{a}	120^{A}	52^{b}	32^{C}	0.021	0.002
	(28)	(18)	(25)	(9)	(30)	(25)	(16)	(9)		
%	73^{ab}	71	75^{ab}	62	90^{a}	72	50^{b}	36	<0.001	0.119
	(5)	(7)	(7)	(5)	(2)	(5)	(9)	(7)		

Fine = fine ash, Coarse = coarse ash. Sig. level = significance leve. Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different vegetation cover types according to post hoc test (Duncan's multiple range test). Small superscripted letters for November sampling, capital superscripted letters for January sampling.

There are three main reasons for the variations in mean gross elemental losses (%): 1) particulate redistribution by wind in situations where the temperature of the burn was always below the volatilization temperature of the given element (Ca and Mg; see section 4.3.1), 2) volatilization in situations where the mean temperature of the burn was always above the volatilization temperature of the given element (C, N), 3) combined effect of volatilization and particulate redistribution in situations where the mean temperature of the burn was lower than the volatilization temperature of burn but the maximum temperature of the burn was higher than the volatilization temperature of the elements (P, K).

Table 4.18 Elemental loads before and after combustion, and fire-induced elemental losses across the northern region of Ghana during December (2002) and February (2003) burns. Data adopted from Bagamsah (2005). n = 10, values are means, standard error of mean in brackets beneath the mean.

	Savanna		Woody savanna		Grassland		Shrubland	
	Dec	Feb	Dec	Feb	Dec	Feb	Dec	Feb
	Elemental load prior to combustion (kg km^{-2})							
C*10^3	279	136	288	313	295	349	227	158
	(26)	(7)	(26)	(30)	(19)	(2)	(22)	(11)
N	2600	1400	2700	2600	2500	2700	2300	1600
	(224)	(100)	(168)	(227)	(142)	(112)	(209)	(156)
P	261	102	946	800	439	600	277	85
	(75)	(6)	(79)	(116)	(141)	(50)	(98)	(9)
K	870	620	1750	1400	1770	1260	980	670
	(87)	(33)	(176)	(185)	(189)	(88)	(108)	(55)
Ca	2020	500	1560	1800	1870	2800	1949	600
	(229)	(36)	(224)	(235)	(240)	(147)	(220)	(54)
Mg	600	800	790	1200	156	1236	718	1000
	(98)	(54)	(120)	(108)	(8)	(77)	(189)	(90)
Na	66	24	120	44	187	86	58	34
	(16)	(2)	(13)	(6)	(10)	(9)	(8)	(3)
	Elemental load in ash (kg km^{-2})							
C*10^3	15	15	14	13	31	9	13	15
	(1)	(5)	(2)	(2)	(1)	(1)	(1)	(2)
N	210	143	171	378	210	250	134	172
	(21)	(17)	(24)	(58)	(31)	(30)	(14)	(20)
P	67	49	141	268	158	231	85	57
	(3)	(4)	(20)	(37)	(16)	(38)	(11)	(6)
K	430	458	298	575	1017	570	537	397
	(20)	(27)	(75)	(87)	(122)	(69)	(43)	(48)
Ca	486	363	400	471	577	1091	954	278
	(26)	(49)	(89)	(106)	(48)	(132)	(133)	(37)
Mg	200	267	220	324	112	918	150	314
	(27)	(24)	(42)	(39)	(13)	(156)	(19)	(33)
Na	18	14	23	17	60	17	26	23
	(1)	(2)	(4)	(4)	(5)	(1)	(1)	(2)
	Elemental loss(kg km^{-2})							
C*10^3	264	121	277	300	264	339	216	142
	(26)	(7)	(24)	(31)	(29)	(23)	(22)	(11)
N	2400	1300	2500	2200	2300	2400	2200	1460
	(236)	(101)	(156)	(243)	(156)	(128)	(211)	(165)
P	190	53	830	557	280	331	190	29
	(76)	(7)	(78)	(108)	(135)	(56)	(95)	(10)
K	440	158	1440	840	750	677	440	260
	(89)	(40)	(119)	(194)	(133)	(125)	(81)	(70)
Ca	1530	161	1160	1280	1290	1726	990	296
	(238)	(44)	(211)	(180)	(246)	(216)	(256)	(65)
Mg	420	489	610	860	50	320	560	690
	(99)	(60)	(188)	(118)	(17)	(98)	(191)	(101)
Na	48	10	98	27	130	70	35	11
	(17)	(2)	(14)	(5)	(12)	(9)	(7)	(4)

Dec = December, Feb = February, DBLF = Deciduous broadleaf forest

This assumption is supported by the modeled relative elemental losses in particulate and non-particulate forms (Figure 4.5, 4.6 and 4.7).

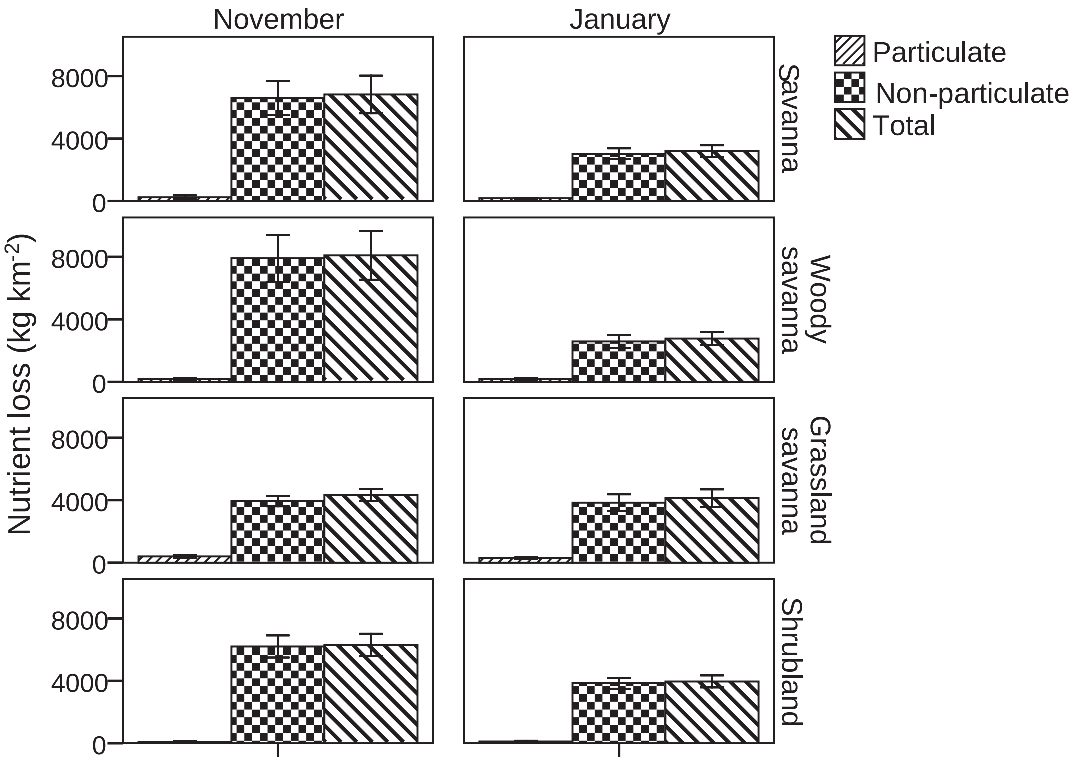

Figure 4.5 Distribution of particulate and non-particulate fire-induced elemental nitrogen losses across different vegetation types during vegetation-burns in November 2010 and January 2011 across the northern region of Ghana. Bars represent the standard error of mean

Non-particulate transfers of N and C across all vegetation types are multiples of the particulate transfers in both November and January burns. Ca and Mg on the other hand are lost in the particulate forms in both months. Losses of P, K and Na in either particulate or non-particulate form depends on the vegetation type on which the burn occurs and also the month of the burn. The high P loss in non-particulate form compared to the particulate losses across shrubland and savanna vegetations in both months, and across the woody savanna vegetation during November burns is attributed to the high maximum temperature of burn during these fires (Table 4.2). The K losses are in particulate forms across all vegetation types, but the relatively high non-particulate loss of K across shrublands in January could not be explained.

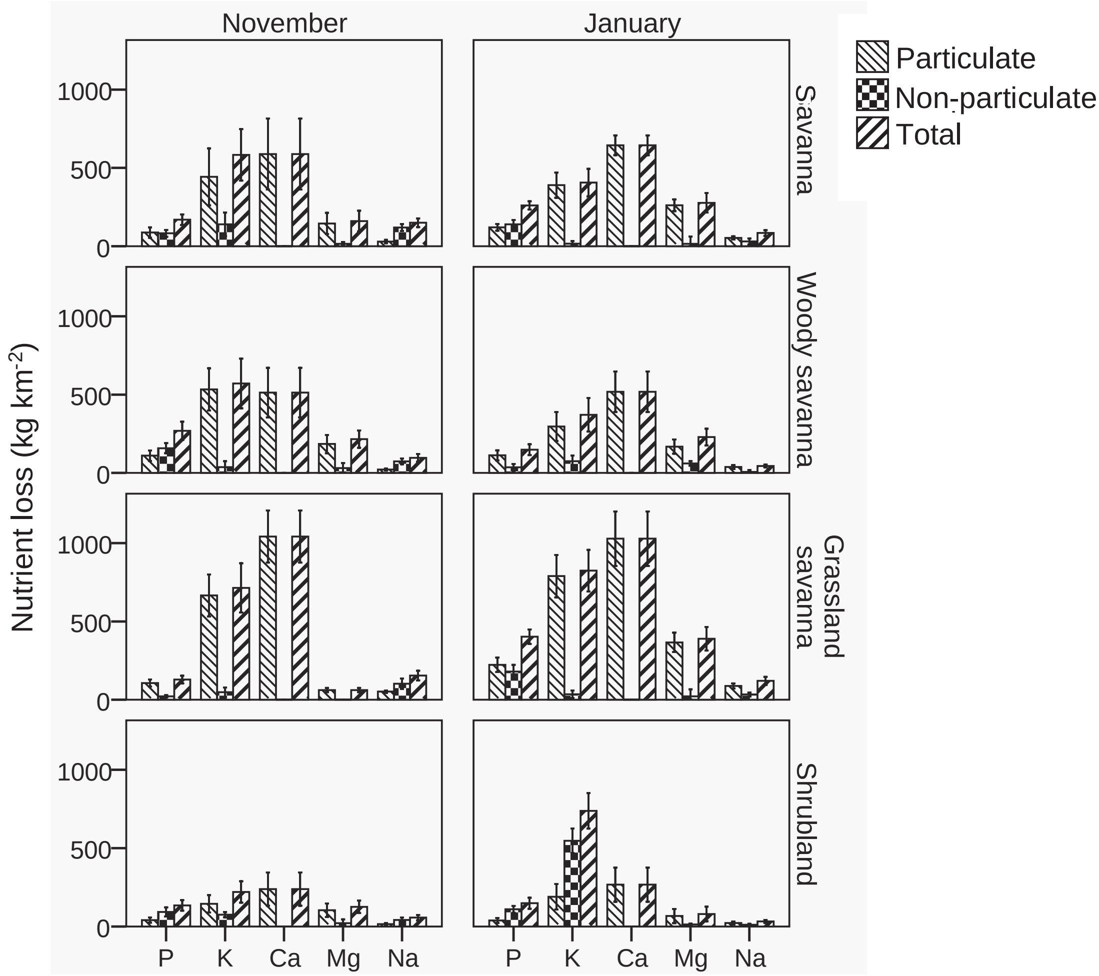

Figure 4.6 Distribution of particulate and non-particulate fire-induced plant nutrient losses across different vegetation types during vegetation-burns in November 2010 and January 2011 across the northern region of Ghana. Bars represent the standard error of mean.

In the case of P and K, the proportion of nutrients actually volatilized and hence lost to the atmosphere to the proportion redistributed in particulate form depends also on the duration when the temperature of the burn exceeds the volatilization temperature of the elements. The longer the duration at this temperature, the higher the K and P losses attributable to volatilization (Misra et al. 1993). The duration of the burn at temperatures above the volatilization temperatures of P and K could, however, not be recorded during the study.

The highest N losses of 8.1 Mg km^{-2} in November across the woody savanna site are attributed to the high herbaceous stratum and the high herbaceous N concentration of 19.8 mg g^{-1} (Table 4.7) compared to the low herbaceous N concentrations of other vegetation types.

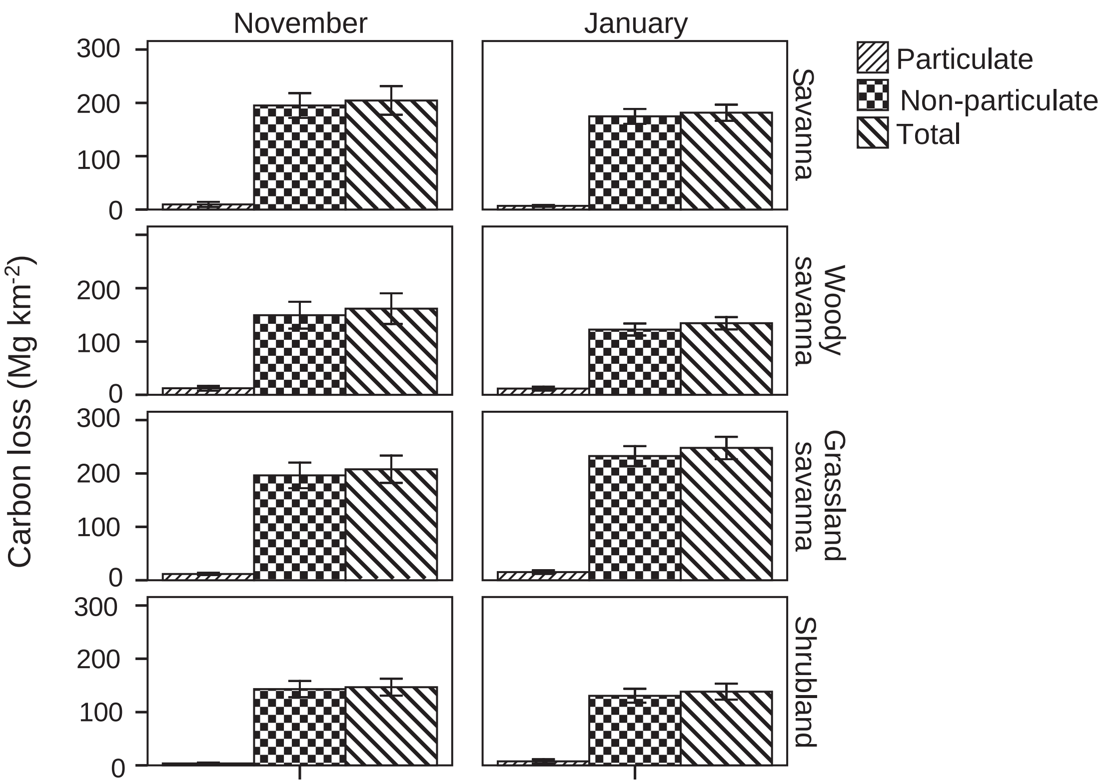

Figure 4.7 Distribution of particulate and non-particulate, fire-induced elemental carbon losses across different vegetation types during vegetation-burns in November 2010 and January 2011 across the northern region of Ghana. Bars represent the standard error of mean.

The high concentration could be attributed to a relative moisture buffering effect of trees that maintain comparatively good soil moisture across this vegetation type at the onset of the dry season. This may result in enhanced soil microbial activity and soil productivity. Between 2.8 and 8.1 Mg km^{-2} N are estimated to be variously lost during burns across the region (Table 4.12). The estimated N losses due to burn is about 3 times that estimated by Bagamsah (2005) for the 4 most common (section 3.3) natural vegetation covers during December and February burns across the northern region of Ghana (Table 4.18).

This observed difference is due to the relatively low plant tissue N concentration recorded by Bagamsah (2005) compared to values recorded in this study (section 4.3.3). While Na losses were higher in this study, fire-induced P, K, Ca, and Mg losses (kg km^{-2}) were generally lower than values estimated by Bagamsah (2005).

4.3.5 Indirect after-fire ash elemental losses and ash ecological impact

Besides the direct elemental losses in particulate and non-particulate forms that occur during fires, the nutrients left in settling ash may leach to lower horizons beyond plant root uptake (Soto and Diaz- Fierros 1993; Stark 1977), be eroded by wind or runoff from the burned site (Núñez-Delgado et al. 2011; Wells et al. 1979; Debano and Conrad 1978) to a different geographic location, mineralized or lost through after burn ash convection (Úbeda et al. 2009). This results in a net reduction in fertility of the burned site. The increase in vulnerability of ash-retained nutrients to after-fire losses further increases the susceptibility of the region to losses in soil productivity. The components of ash nutrients that are not lost through any after-fire loss mechanisms remain in the soil but go through processes that may render them relatively unavailable for plant uptake. In the soil, the high contents of ash P, K, Ca, Mg, and Na increase the level of these elements immediately after the burn resulting in an increase in their short-term availability for uptake by plant roots (Kutiel and Inbar 1993). Consequently, there is an increase in vegetative growth per precipitation event, in which case nutrients might be relatively conserved in plant tissues. The problem associated with this acute nutrient availability as captured by van der Waal et al. (2011) is that only herbaceous plants and grasses could make good use of it at the expense of trees, which require the nutrients at a coarser temporal distribution. Fire-induced acute nutrient availability after burns may subsequently be a prime factor in the establishment of grasslands and savanna across the landscape.

Also, P in ash exists primarily as Ca polyphosphates (Ranalli 2004) with low water solubility and soil mobility, but they become soluble upon neutralization of the ash alkalinity. This occurs mostly in acidic soils, resulting in high extractable P for plant uptake (Raison and McGarity 1980). The high P-sorbing nature of the native soils across the study area (Owusu-Bennoah et al. 1997; Owusu-Bennoah et al. 1991; Owusu-Bennoah et al. 2000) will however decrease the P mobility and availability after it has been adequately dissolved. This will further decrease the potential for P uptake by plants and thus render them vulnerable to further losses. The difficulty that might be associated with the plant uptake of remaining ash P also has synergistic effects on the uptake of other nutrients (K, Ca, Mg, Na), though these other nutrients might be comparatively readily available in the soil.

The large ash amounts, resulting from burns has effects on adjacent stream water quality and on general environmental pollution. The effect of burned ash and the nutrients it contains on stream bodies is enhanced by the degree of organic matter combustion, rainfall occurrence after fires, slope and distance of the burned location from the water body, wind condition during and after fire, and the cation exchange capacity of the soil (Ranalli 2004). Debano (2000) suggested the hydrophobic organic layers formed in soils during fires to repel water molecules, thereby increasing runoff and nutrient transport into water bodies. The high P, K, Ca, Mg, and Na content of ash increases the P concentration in adjacent sink streams. Occurrence of this phenomenon in P-limiting water bodies results in a sudden increase in stream algal growth and oxygen consumption. This could promote sudden eutrophication of adjacent water bodies in this water-scarce region of the country. The resulting reduction of residence oxygen available for fish leads to death of aquatic life. Reduced water oxygen also results in chemical reduction of metal oxides and release of residence heavy metals from bottom sediments into the main water column. Besides, the fire-associated dissolved organic carbon may form carcinogenic trihalomethanes (e.g., the haloform reaction) during halogen disinfection/water treatment for human consumption. These phenomena may impact water quality for general public consumption and ecosystem productivity.

4.3.6 Seasonal and annual direct gross plant nutrient losses due to bush fires

Because the vegetation classification of Bagamsah (2005) generally falls in line with the IGBP classification of vegetation cover classes used in this study (section 3.3.1), the December and February elemental-loss estimates by the author (Table 4.18) were adopted together with the estimated values for November and January (section 4.3.4) in order to quantify the gross annual losses across the northern region during the fire season (equation 3.7). The elemental losses for each vegetation type were then extrapolated to similar vegetation classes across the entire Ghana.

The magnitude of gross elemental loss by vegetation type for all nutrient elements (P, K, Ca, Mg, Na) except N generally followed a pattern similar to that of the relative area of vegetation-burn and the monthly burned area (Appendices 4, 5 and 6). The order of gross nutrient loss amount was savanna > woody savanna >

cropland/natural vegetation mosaic > grassland > shrubland, and the order of monthly nutrient losses was December > November > January > February (Table 4.19).

Table 4.19 Gross annual and inter-seasonal transfers of carbon and plant nutrients due to bush fire occurrence across the northern region of Ghana and across Ghana. Values are 95% confidence interval of mean estimated from field quantified gross elemental loss per unit area across the study area and the seasonal area of each vegetation-burned over a 10-year period (2001-2010). Seasonal inter-vegetation type burns are provided in Appendices 4, 5 and 6.

Element	November		December		January		February		Annual Total	
	Low	Upp	Low	Upp	Low	Upp	Low	Upp	Low	Upp
Northern region of Ghana (Gg)										
C	730	2860	4400	9760	270	1200	20	140	5430	14000
N	22	104	40	88	4	23	0	1	66	216
Ghana (Gg)										
C	1660	5500	6490	15000	480	3180	60	340	8680	24000
N	49	198	59	135	8	66	1	3	116	401
Northern region of Ghana (Mg)										
P	500	2750	2090	13080	360	1740	9	100	2960	17700
K	1300	10100	7300	23000	400	3400	10	270	9031	37000
Ca	730	11500	21200	59860	887	4545	21	320	22800	76000
Mg	160	3200	4600	20000	270	2300	60	560	5100	26000
Na	460	2260	430	2700	80	640	1	15	970	5600
Ghana (Mg)										
P	1100	5200	4200	22000	600	4700	46	460	6000	33000
K	2900	19400	12500	39300	770	10700	80	900	16200	70400
Ca	1660	22200	30400	90000	1500	14000	180	1400	33700	128000
Mg	350	6200	6700	31800	500	6300	110	1080	7800	44500
Na	1030	4370	750	4340	140	1550	7	50	1930	10300

Low = lower bound, Upp = Upper bound, distribution = Delta distribution with a modified Bessel function of the second order

The observed order of nutrient loss is due to comparable seasonal elemental concentrations that limit elemental losses to the absolute quantity of combusted fuel load and the area of vegetation-burn. The higher the area burn, the higher the combusted element in fuel load and the higher the elemental losses per unit area. Nitrogen losses did not, however, follow this pattern, as losses in November of 22-104 Gg were comparatively higher than the losses of 40-88 Gg in December, though about 3 times the area burned in November (21%) is that burned during December burns (68%; section 3.3.3) across the northern region.

Similarly, December burns across entire Ghana (58%) constitute about twice the area burned in November (24%) but result in lower N losses of 59-135 Gg compared to losses of 49-198 Gg in November. The comparatively high N loss in November is attributed to the high November tissue N concentrations, particularly across savanna vegetation. The N losses of 22-104 Gg were higher in November compared to the 40-88 Gg in December across the northern region (and similar observation for entire Ghana).

Nitrogen volatizes easily during the burns (Figure 4.5), and hence is lost completely to the atmosphere in gaseous form (Caldwell et al. 2002). Some P and K may also volatilize during burns (Figure 4.6) and be lost to the atmosphere when the volatilization temperature is exceeded (section 4.3.1). The unvolatilized P and K, together with Ca, and Mg may, however, be redistributed in particulate form across the study area (Binkley and Christensen 1991; Bagamsah 2005). In the particulate form, dry-season, unpredicted atmospheric currents could carry the transferred nutrients further away from their geographic source. This phenomenon has a potential negative impact on temporal soil fertility across burned sites. The consistent occurrence of annual fires and the related plant-nutrient transfers consequently contribute to the decline in soil fertility reported across the study area by Vlek et al. (2010).

Total fertilizer import into Ghana was about 123 Gg in 2007 (Banful 2009) rising to an estimated 170 Gg in 2009. In 2007, 15.7 Gg elemental N, 2.4 Gg elemental P, and 6.3 Gg elemental K were imported. Using 2007 as baseline year, gross N losses due to bush fires are about 7.5-25 times the amount imported into the country in the form of fertilizers, P loss about 2.5-14 times, and K losses about 2.5-11 times. Fire-induced nutrient losses consequently mean tremendous economic losses to the nation. Any attempt that aims to reduce bush fires will serve as a comparatively cheap, in terms of fertilizer cost, labor cost and time of fertilizer application, and economically viable compensation to long-term soil fertility and regional food security across the area.

4.3.7 Seasonal and annual gross carbon losses and gaseous emissions during bush fires

As with nutrient losses, fire-induced C loss amounts corresponds to the area of vegetation-burned in terms of vegetation type and month of burn (Table 4.19; also see Appendix 4). Van der Werf et al. (2010) estimated the mean global and the continental African pyrogenic C emissions to be 2013 Tg and 1038 Tg per year, respectively, from 1997 to 2009. The estimated annual bush-fire C emission across Ghana is 0.9% to 2.3% of the estimated pyrogenic C emissions across entire Africa, and 0.44%-1.2% of the average annual global C emissions. Lehsten et al. (2009), on the other hand, estimated the C emission between 2001 and 2006 across Africa to be 723±70 Tg $year^{-1}$. Williams et al. (2007) estimated fire emissions associated with deforestation, shifting cultivation, burning of agricultural residues, and fuelwood to be 0.4 Pg C $year^{-1}$ across entire Africa. The estimated carbon emission across Ghana is about 2 to 6% of total African estimates by Williams et al. (2007).

Emission factors used to estimate the burn-related gaseous emissions (equation 4.8) are provided in Table 4.20.

Table 4.20 Emission factors (g of emitted compound kg^{-1} of biomass burned) used to estimate gaseous emissions due to vegetation fires across vegetation types. Factors based on measurements made in smoke that has cooled to ambient temperature but that has not yet undergone significant photochemical processing. Data adopted from Akagi et al. (2011) and Wiedinmyer et al. (2011).

Emission	Savanna		Woody savanna		Grassland		Shrubland	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
CO_2	1692	37	1710	39	1692	37	1710	39
CO	59	16	67	13	59	16	67	13
CH_4	1.5	0.7	2.51	0.72	1.5	0.7	2.51	0.72
NO_x	2.8	0.65	3.26	0.95	2.8	0.65	3.26	0.95

The emission factors are comparable to those in other estimates across similar vegetation types (Scholes 1995; Andreae and Merlet 2001; Sinha et al. 2003; Scholes and Andreae 2000; IPCC 2006). The commonly used IPCC (2006) emission factors were not used because they only provide a single factor to be used for all vegetation types across the savanna region, which might not reflect the differences in fuel characteristics and hence emissions across the different vegetation types.

The estimated fire-induced annual/monthly greenhouse gas (CO_2, CH_4) and gaseous pollutant (CO, NO_x) emissions are provided in Table 4.21 (see also Appendices 7 and 8 for the monthly inter-vegetation cover type emissions). As in the nutrient loss estimates, the quantities of gaseous emissions follow the pattern of area burns across the various vegetation types and according to the area burned in a given month. Highest CO_2, CO and CH_4 emissions occur on savanna vegetation and in December, with lowest emissions occurring in February and across shrubland vegetation. The estimated CO_2 and CH_4 emissions correspon to a total CO_2 equivalent, global warming potential greenhouse gas emission of 21- 60 Tg year^{-1} across the northern region of Ghana and 33.4-103 Tg year^{-1} across Ghana.

The estimated national CO_2 emissions are 1.4 - 4.5% of the global CO_2 emissions that are due to land-use change (Friedlingstein et al. 2010). The estimated amount of CH_4 emissions is very important considering the high global warming potential compared to CO_2 (Howarth et al. 2011).

Table 4.21 Gross annual and inter-seasonal gaseous emissions (Gg) due to bush fire occurrence across the northern region of Ghana and across Ghana. Values are 95% confidence interval of mean estimated from field-quantified combusted fuel loads, mean seasonal area of vegetation burned over a 10-year period (2001-2010), and the respective emission factors per vegetation type. Seasonal inter-vegetation type emissions provided in Appendices 7 and 8.

	November		December		January		February		Annual Total	
	Low	Upp	Low	Upp	Low	Upp	Low	Upp	Low	Upp
Northern region of Ghana										
CO_2	2900	12300	16700	39200	1100	5100	74	540	20700	57200
CH_4	1	25	4	80	0.2	11	0.0	1	4	118
CO	36	610	230	1900	13	250	1	27	280	2800
NO_x	4	38	23	120	2	16	0.1	2	29	175
Ghana										
CO_2	6500	23700	24600	60000	1900	13600	230	1400	33200	99000
CH_4	1	50	6	126	1	30	0.1	3	8	200
CO	80	1160	350	3000	28	680	3	70	470	4900
NO_x	9	70	30	190	3	40	0.3	4	45	300

Low = lower bound, Upp = Upper bound, distribution = MeijerG function

Though some of the emitted CO_2 might be balanced through atmospheric CO_2 removal by annual photosynthetic processes across each vegetation type (which was beyond the scope of this studies), the CH_4 emissions remain in the atmosphere trapping the solar radiation in the earth's atmosphere and contributing to the global warming phenomenon (Shindell et al. 2009). In addition, smoke containing these greenhouse gases reduces direct irradiance at the earth's surface. This cooling effect reduces tree transpiration and water evaporation from the land and ocean surfaces, consequently influencing the earth's hydrological cycle (Papaioannou et al. 2011). Any means of reducing bush fires will reduce the fire-induced emissions of CO_2 and CH_4. Reduced emissions plus storage of the carbon that could have been emitted is a double-win situation regarding climate protection. Furthermore, the carbon storage in the unburned plants would increase in subsequent years, which in turn would increase the absolute C capture in these plants. This triple-gain situation would strengthen the natural buffering capacity of the earth's atmosphere against a change in the long-term climate.

Given the relatively small size of Ghana, the high quantities of fire-induced gaseous emission calls for concern for the global climate (Crutzen and Andreae 1990; Friedlingstein et al. 2010; Howarth et al. 2011): Particularly so across the northern region, where most of the emissions per year occur. Since CO_2 emissions from fires and also from combustion of fossil fires are removed by plants in the process of photosynthesis, there is the need to exploit fire control measures and enhanced tree growth for C capture and storage for a sustainable climate.

4.3.8 Reducing direct fire-induced nutrient losses and gaseous emissions

Principles underlying nutrient loss reduction

In order to formulate the most efficient means to burn the vegetation with minimum elemental losses and gaseous emissions, early burn (November) elemental losses per unit burn area were compared with those of late burns (January) (Table 4.22). See also Table 4.3 for seasonal comparisons per vegetation cover type. There was no significant difference between of K, and Ca losses during November burns and the amount of these elements lost during January burns. In contrast, significant differences exist between the quantities of N, P, Mg and Na that are transferred to the atmosphere during early burns and those transferred during late burns. Nitrogen and Na losses are higher during the early burns, while P and Mg losses are higher during the late burns. The difference in losses is attributed to the variation in combusted fuel load (section 4.3.2) and tissue elemental concentrations (section 4.3.3).

The results indicate a trade-off in nutrient conservation between N plus Na on the one hand and P plus Mg on the other hand regarding the effect of season on nutrient losses (Table 4.22). The choice of which nutrient to conserve depends on the most limiting nutrient across the landscape and the general availability of the given nutrient. Late burns should be encouraged for conservation of fire-induced N and Na losses (Table 4.22).

Table 4.22 General t-tests of statistical difference in elemental losses (kg km^{-2}) between early (November) burn and late (January) burn during bush fire occurrence across the northern region of Ghana. The tests for each vegetation type are provided in Table 4.3.

	November		January		t	Sign. level
	Mean	Std dev	Mean	Std dev		
Gross elemental losses						
N	6300	3570	3520	1440	4.5	<0.001
P	170	130	250	150	-2.2	0.032
K	560	460	650	360	-0.9	0.379
Ca	740	570	680	460	0.6	0.542
Mg	170	150	290	200	-2.6	0.014
Na	115	80	77	60	2.7	0.010
C	178000	80000	175000	65000	0.2	0.835
Plant tissue moisture and ash loads						
% tissue moisture[1]	38	17	25	19	5.2	<0.001
Ash load	86000	44000	60000	21000	3.8	<0.001

N = 40, [1]n = 89, Sign. Level = significance level, Std dev = standard deviation of mean

However, given the high P binding sesquioxide contents of the prevailing soils (Owusu-Bennoah et al. 1997; Owusu-Bennoah et al. 2000), the projected reduction and depletion of rock phosphates used in the manufacture of P fertilizers (Dawson and Hilton 2011), and the general inability to fix any external P into soils compared to biological N_2-fixation (Elser 2012), reducing P losses through fires is of utmost importance across the region. In this regard, early burns across the region should be promoted, these are associated with significantly lower P losses per unit burned area when compared to late burns. This is particularly so across savanna vegetation covers (Table 4.3) which constitutes about 88% of the burned area across the northern region; P losses are about 170 kg km^{-2} and 261 kg km^{-2}, respectively, during early and late burns (Table 4.13).

Principles underlying gaseous emissions reduction

NO_x emissions are higher during the early fire season than in the late fire season (Table 4.23). This is due to the high early-season absolute tissue N amount and N losses (Table 4.12). The similar late burn and early burn C-related emissions are attributed to the insignificant effect of the burn season on C losses (Table 4.22, Table 4.3). Similarly, the quantity of carbon-related emissions per unit burn area for early and late burns means that the area of burn is the main determinant of total carbon-related emissions. This explains why savanna vegetation and the month December are associated with high total emissions of carbon-related gases. During the early burns, emissions per unit burn area of all gases are highest across savanna vegetation (Table 4.23). In the late burns, however, emissions are highest across grassland vegetation.

Table 4.23 Gaseous emissions of early and late season bush fires across Ghana estimated from the combusted fuel load (kg km^{-2}) and emission factors (g of gaseous emissions kg^{-1} of combusted fuel load; Akagi et al. (2011), Wiedinmyer et al. (2011)). Values are 95% confidence interval of mean.

	CO_2 (Mg km^{-2})		CO (Mg km^{-2})		CH_4 (kg km^{-2})		NO_x (kg km^{-2})	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Early fire season								
Savanna	600	1100	7	54	100	2270	860	3440
Woody savanna	460	990	12	51	310	2170	390	2830
Grassland	590	1050	7	51	100	2140	850	3250
Shrubland	460	750	12	39	310	1650	390	2160
Late fire season								
Savanna	640	920	8	45	110	1890	930	2870
Woody savanna	450	680	11	35	300	1490	380	1940
Grassland	740	1120	9	55	130	2300	1080	3490
Shrubland	490	720	12	37	330	1580	415	2060

Because early burns are associated with comparatively high fuel load moisture content, better plant growth condition and high absolute N content of combusted fuel load (Table 4.12 and Table 4.3), they are associated with high N losses per unit burned dry matter. However, the high moisture content also impedes burn occurrences, resulting in patches of burned and unburned lands that promote wildlife and sustain the productivity of the ecosystem. Early burn also reduces combustible fuel load availability for late burn occurrence and could be adopted to enhance tree growth across the region. On the other hand, the comparable combusted fuel load C between early and late season (Table 4.3) coupled with the low late season fuel load moisture content enhances fire spread during the late fire season making late-season burns susceptible to higher gaseous emissions with the associated health and environmental consequences (Papaioannou et al. 2011; Langmann et al. 2009; Lehsten et al. 2009).

The findings therefore identify two economically (labour, time, cost) efficient priority investments for reducing fire related emissions. Savanna and woody savanna vegetation are associated with trees at different stages of growth. Some are established enough to withstand the adverse effects of annual fires while seedlings are not. Tree seedling establishment in savanna and woody savanna vegetation are hindered by fires, (Duncan and Chapman 2003; Sankaran et al. 2004) thereby reducing the temporal C sequestration potential. Burn prevention in savanna and woody savanna vegetation must be of utmost concern to protect and encourage the establishment of young seedlings. Besides, burns across savanna vegetation are also associated with relatively high emissions.

Though comparable emissions per unit burn area occur in both seasons across the same vegetation cover, the emissions in the early season are reduced due to reduced burns in the moist vegetation. Late burn leads to a large total area burn due to the enhanced combustibility created under the reduced late-season tissue moisture conditions. This knowledge could also be exploited in two scenarios with regard to emission reduction. First, early burns could be prevented, avoiding the higher N-related emissions per unit burn fuel load. However, the subsequent late burns will be associated with high amounts of easily combustible fuel load that puts the entire vegetation-burn system in a vulnerable state. The benefits associated with early burn prevention are therefore minimal.

On the other hand, early-season controlled bush burning could reduce late burn occurrence and minimize the associated total annual emissions. The patches of burned and unburned vegetation created by early burns also promote the ecosystem's natural sequestration ability by enhancing natural tree seedling establishment to ages when these become relatively resistant to fire related heat stress. The timing of such burns is critical, as burns towards the mid dry season will result in complete combustion, comparable to the late season burns. The first week of November is the best time for the controlled early burns. At this time, vegetation moisture is high, and there is reduced fire spread due to the associated low combustibility. This results in higher proportions of unburned vegetation patches than burned patches, and offers relatively buffered environmental conditions for flora and fauna.

Fire-related CO_2 emissions across grasslands are thought to be balanced by annual plant regrowth. This hypothesis may not entirely hold because during the reconnaissance survey of vegetation distribution, it was observed that some trees almost always exist across grasslands. Burns limit the growth and establishment of seedlings of these grassland trees, which could have increased the C-storage capacity of the system. Besides, burn affects two entirely different CO_2-related phenomena: Emission and sequestration, both of which could be exploited in C retention, harvest and storage. For instance, when fires are prevented, not just a reduction in frequency, emissions that are directly associated with the burns are curbed. Tree stands consequently develop extra potential through growth for CO_2 removal in subsequent years, which is not same if those trees were burned in preceding years at the seedling stage.

Socio-ecological concept of nutrient loss and emissions reduction

From the perspective of reducing nutrient losses, greenhouse gas emissions and simultaneously increasing carbon sinks, vegetation burning needs to be controlled. Intense late burning consumes an enormous fuel load. Controlled early burns should be encouraged, as these have relative advantages in terms of nutrient conservation, emissions reduction, tree growth promotion and habitat protection for wildlife. Nonetheless, “carbon farming” could also be promoted across the region, where families/households are encouraged to own parcels of reserved land which they manage themselves. Trees grown in such farms would quickly absorb CO_2 from the atmosphere while reducing direct emissions due to fire. Such trees could be harvested as timber or incorporated into the soil through slash and mulch after some years: a form of carbon harvesting and soil carbon storage. A foreseen problem in this kind of storage is a situation of accidental fires when stored carbon is consumed and emitted in the process. Tropical savanna trees are known to generally adapt to bush fires and easily recover from burn stress (Bond and Midgley 2012; Gignoux et al.2009). Such accidental fires only consume the litter fuel load. Global carbon sink is also suggested to double in area in a world without fires particularly across the African savannas (Bond and Keeley 2005).

Since burns, however, serve as an easy means of land preparation, hunting for wild game, and general socio-cultural existence of local communities during the dry season, adoption of alternative options to these livelihoods rather than the use of fire is essential in this regard. Land preparation without burn (Denich et al. 2004), though expensive, needs to be encouraged. Davidson et al. (2008) compared greenhouse gas emissions between slash-and-burn land preparation with the emissions associated with slash-and-mulch land preparation, and found a reduction in greenhouse gas emissions in the latter. Cutting down plants at the onset of the dry season and leaving the plant debris on the surface of the soil could reduce fire occurrence, improve soil nutrition/physical properties, and increase the soil-carbon sequestration process. These, undoubtedly, are herculean tasks for the local people and may require external motivation for successful implementation.

Institutions and incentive packages could play major roles in the control of bush fires in this regard. Collaborative education by governmental institutions, NGO's (Non-Governmental Organizations), representatives of FBO (Farmer Based Organizations), local representatives and local chiefs on existing bush fire policies and adoption of any such emission reduction/sequestration strategies needs to be encouraged. For the global nature of greenhouse gas impacts, adequate incentive packages could be given to communities that register observed reductions in spatio-temporal bush fire occurrence. Douglass et al. (2011) discussed the use of carbon credits in savanna land management and biodiversity conservation, where they also argued that the cost of management for carbon sequestration could be minimized through the sale of carbon credits. Local bush fire control across Ghana therefore serves as an avenue for investment in the growing carbon market and for purchase of carbon credits by emitting companies and entities to offset their carbon footprint. This will, however, require adequate spatio-temporal monitoring of bush fire occurrence by existing institutions.

4.4 Conclusion

The high amount of nutrients that are left in ash after combustion are susceptible to convection by wind currents, to leaching and to erosion losses. Together with direct elemental losses that occur during vegetation fires, these factors reduce the long-term productivity of soils and cause acute/short-term eutrophications in adjacent water bodies. While Mg and Ca are not volatilized during burns, N, P, K and Na may volatilize, since the maximum temperature of the burns exceeded the volatilization temperatures of these elements. Elemental losses during fires are multiples of the quantity annually imported into the country in the form of fertilizers, making fire-induced nutrient losses significant economic losses to the nation. Generally, the higher the burned leafy component, the higher the elemental losses due to high absolute amounts of nutrients in leaves. Similarly, because early burns are associated with comparatively high-fuel load moisture content, better plant growth condition and high absolute elemental content, they lead to high elemental losses per unit burned dry matter. However, the high moisture content impedes burns, resulting in patches of burned and unburned land that promotes wildlife sustenance and reduces the potential occurrence of late-season burns. This phenomenon could be adopted to enhance tree growth across the region. Low late-season fuel load moisture content enhances late burns, leading to higher gaseous emissions with consequences for human health, environment, global climate and natural hydrological cycle. Low percentage combustion of carbon stored in woody parts of plants suggests enhanced tree growth across the region as an efficient means of carbon storage, since carbon stored in the woody parts of trees is not loss during combustion.

5 WET/DRY NUTRIENT DEPOSITS AND NET NUTRIENT BALANCE ACROSS THE NORTHERN REGION OF GHANA

5.1 Introduction

The estimated annual fire-induced plant-nutrient transfers (section 4.3.6) are likely to have deteriorating impact on soils of the northern region of Ghana and cause a decline in soil productivity as suggested by Vlek (1993). Unless a natural plant nutrient balancing mechanism exists, this would continue to have effects on current and future soil productivity parameters. Wet and dry atmospheric depositions, described in chapter 2 are considered to be major mechanisms of plant nutrient return. These returns may fully or partially balance the fire- induced nutrient transfers.

Rainfall contains substantial amounts of plant nutrients (Emmerich 1990; Waterloo et al. 1997; Pelig-Ba et al. 2001), playing a major role in the plant nutrient cycle. Atmospheric nutrients from many sources, including fire-induced nutrient transfers, dissolve in rainwater and settle on soils or vegetation, providing nourishment to plants. For instance, rainfall analyzed at three locations around Obuasi, south of the current study area, by Akoto et al. (2011) was found to contain 0.01-0.42 mg l^{-1} NO_3^- , 0.43-0.74 mg l^{-1} K, 0.56-1.02 mg l^{-1} Ca, 0.15-0.36 mg l^{-1} Mg, and 0.08-0.52 mg l^{-1} Na. Wet deposition, therefore, contributes to soil and crop productivity and hence to the general growth and productivity of the ecosystem.

Dry deposition is also an essential source of plant nutrients across West Africa (Stoorvogel et al. 1997). Annual harmattan-dust deposits and nutrient deposition have been reported for various sites in West African. Mctainsh (1980) reported a dust deposition value of 990 kg ha^{-1} across northern Nigeria for the 1978/1979 harmattan season. As much as 2000 kg ha^{-1} $year^{-1}$ and 365 kg ha^{-1} $year^{-1}$ of dust is estimated to annually accumulate in the Sahelian zone and the Guinea zones of West Africa, respectively (Orange et al. 1993). Stoorvogel et al. (1997) reported dust deposition of up to 80 kg ha^{-1} $year^{-1}$, and the plant nutrients potassium (K), phosphate (P), calcium (Ca), and magnesium (Mg) in harmattan-dust particles to be about 2.5 kg ha^{-1} $year^{-1}$, 0.11 kg ha^{-1} $year^{-1}$, 3.5 kg ha^{-1} $year^{-1}$, and 0.4 kg ha^{-1} $year^{-1}$, respectively, across the Tai National park in Cote D'Ivoire. Comparatively higher dust deposits of 150 kg ha^{-1} $year^{-1}$, and higher dust nutrient deposits of 3 kg K ha^{-1} $year^{-1}$, 4 kg Ca ha^{-1} $year^{-1}$, 1.4 kg Mg ha^{-1}

year^{-1}, and 0.6 kg Na ha^{-1} year^{-1} have been reported in the more eastern Ghanaian town of Nyamkpala by Tiessen et al. (1991). Though mostly attributed to harmattan-dust, these nutrient depositions may arise from the interplay of three important phenomena: harmattan wind (He et al. 2007), return of burned plant debris (section 4.3.6), and local dust redistribution (Lyngsie et al. 2011).

The dust-laden northeasterly harmattan wind (Engelstaedter et al. 2006) that blows from the Bilma, Faya-largeau and/or Bodélé depression of the Saharian Chad basin (Tiessen et al. 1991; Giles 2005; Washington et al. 2003) between November and March of each year (Figure 5.1) carries nutrients from their sources of origin.

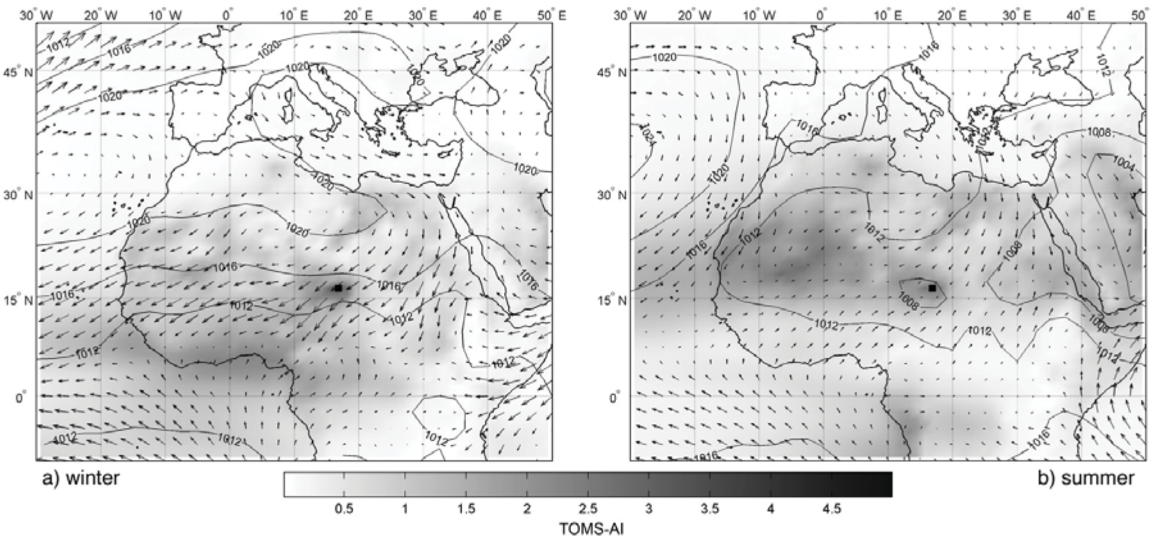

Figure 5.1 Mean annual atmospheric mineral dust concentrations quantified by TOMS (Total Ozone Mapping Spectrometer on the Nimbus satellite) aerosol index (dimensionless) and NCEP/NCAR horizontal wind vectors at 925 hPa in winter (December to February) and summer (June to August) during the years 1978-1993. The black square indicates the location of the Bodélé Depression. Adopted from Schwanghart and Schütt (2008).

Dust mobilization during the harmattan season is highly dependent on air pressure variability in the Mediterranean. High pressure to the north of the Bodélé depression is reported to intensify the North East trade winds leading to an increased dust entrainment, mobilization, transport (Washington and Todd 2005; Washington et al. 2006; Schwanghart and Schütt 2008) and subsequent deposition across Ghana, where it also reduces relative humidity and temperatures. Dusts pose respiratory health hazards to inhabitants and also reduce visibility, endangering road and air traffic. The entrained dusts have been observed not only to be deposited in Ghana but as far as the Atlantic and the Amazonian region (Dunion and Velden 2004; Koren et al. 2006). Dust is reported to be resupplied to the Bilma and Faya-largeau region from the Tibesti mountains through Aeolian and fluvial activities (Kalu 1979). Annual occurrence of the harmattan wind results in cyclic deposition of dust particles and their constituent plant nutrients across most countries of West Africa.

Local dust may also be carried some distance away from its source in the harmattan wind plume. It is also during this period that the direct fire-induced elemental transfers and the burned/exposed ash nutrients (section 4.3.4 to section 4.3.6) occur as a result of which fire-induced elemental transfers may also add to the nutrient load and become vulnerable to transport by the prevailing harmattan wind. The fraction of deposited nutrient elements (N, P, K, Ca, Mg, Na) from each source may be difficult to estimate precisely. The fractional mass of bulk dry deposits from each source and their nutrient concentrations may vary from one geographic site to another, dependent on factors such as the distance between a measuring site and the external source/natural burned site, and the harmattan wind direction relative to burned sites/local dusts.

In all cases, however, as nutrient-rich dust particles are transported they settle on soils and water bodies, supplying these mediums with plant nutrients. Hermann et al. (2010) reports nutrient deposition by dust from the north to the south transect of eastern West Africa. Lawrence and Neff (2009) give an in-depth review of dry nutrient depositions across the globe. The contribution by local dust redistribution could be reduced by taking samples at appreciable heights above the ground and at locations with adequate ground cover, limiting nutrient inputs to the harmattan wind and vertical return of burned plant debris.

5.1.1 Problem statement

Though precipitation and dry dusts are known to contain essential plant nutrients, and some literature exists on point dry and wet nutrient deposits across sub-continental West Africa, there are no detailed studies on the geospatial and temporal return of these nutrients across the northern region of Ghana. The geospatial and temporal return dynamics of fire-induced nutrient transfers in sustaining agricultural productivity are not well understood. Total annual elemental returns after fire are also not known, thereby limiting any attempt to quantify the balance due to annual fire-induced nutrient transfers and nutrient returns across the region.

5.1.2 Aims and objectives

The aims in this part of the study are to:

1. Quantify the annual geospatial and temporal return of plant nutrients due to dry deposition during the harmattan season and wet deposition by rainfall across the study area.
2. Estimate the net average annual nutrient balance between annual burning losses and annual atmospheric nutrient depositional gains across the region as an indicator of soil and agricultural sustenance across the study area.

5.1.3 Research questions

The specific research questions aimed at achieving the above objectives are:

1. What are the geospatial and temporal dry depositions during the harmattan season and the wet depositions during the rainy season across the northern region of Ghana?
2. What are the concentrations of plant nutrients (NO_3^-, P, K, Ca, Mg and Na) in dry harmattan season depositions and in precipitation during the wet season?
3. Are there any trends in geospatial and temporal wet/dry deposition of plant nutrients across the study area?
4. What is the net annual plant nutrient balance (gain or loss) across the northern region of Ghana that is directly due to dry-season nutrient losses by bush fire and annual gains by atmospheric deposition?
5. What are the implications of the resulting annual plant nutrient balance to soil fertility and food productivity?

5.2 Materials and methods

5.2.1 Description of wet and dry deposition samplers

A 24 cm surface diameter manual wet, dry and bulk atmospheric deposition sampler (Figure 5.2) was used to collect the monthly nutrient depositions from direct nutrient dissolution by rainfall, dry depositions in the dry season, and the bulk nutrient deposition (made up of both wet deposition and dry deposition).

Figure 5.2 Wet, dry and bulk atmospheric deposition samplers as mounted in the field. a) Entire apparatus as mounted in the field. b) Dry deposition sampler. a) Wet and bulk deposition samplers showing observed biological activity in bulk depositions but no such activity in wet-only depositions.

The sampler consists of three components: A dry deposition component which is opened throughout the dry season and two other separate channeling funnels. The funnels are mounted on two collecting vessels, one for collecting wet deposition and the other for bulk deposition. A thin nylon mesh of about 6 mm was used to cover the opening ends of the samplers to prevent contamination by rodents, birds, insects and plant debris. When there are no rains, the funnel for wet deposition collection is covered with a polythene bag (Figure 5.2c) to prevent dust particles and other impurities from entering it, while its respective collecting bottle is closed to prevent the collected rain water from evaporating and also from getting contaminated. The funnel for collection of bulk deposition is always kept open. This way, direct depositions by rainwater, aerosols, dust particles and burned debris are collected in the bulk deposition samplers. The samplers were mounted together on a wood frame at a height of about 2.5 m above the ground to reduce the redistribution of dust inputs from surrounding soils. The samplers were mounted at locations far away from roads and with enough soil cover as to reduce the impact of the local dust redistribution.

5.2.2 Selection of sampling location

Table 5.1 provides the geographic coordinates at the points of sample collection and names of closest towns and villages.

Table 5.1 Geographic locations of geospatial sampling of wet and dry atmospheric nutrient deposits across the northern region of Ghana from June 2010 to July 2011. Negative values (longitudinal direction) indicate west, positive values indicate east. N indicate northern hemisphere

	Geographic coordinate (degrees)	
Closest town/village	Latitude (N)	Longitude
Wa	10.07323	-2.51051
Gindabuo	9.63379	-2.45941
Sawla	9.27520	-2.41320
Sakpa	8.87270	-2.34728
Banda Nkwanta	8.35081	-2.13776
Nasia	10.1598	-0.80235
Pong Tamale	9.68839	-0.82831
Jeregu	9.33084	-0.72784
Wangasi Turu	8.89339	-0.47636
Meriche	8.44817	-0.52898
Katani	10.16495	-0.08197
Piong	9.63875	-0.06409
Adibo	9.24301	0.01785
Bimbila	8.84678	0.05967
Katajel	8.39994	0.02838

A modified stratified contiguous unit-based spatial sampling (Stratified CUBSS, Sahoo et al. 2006) technique was used in this study. The technique is based on Tobler's First Law of Geography, which argues that for a given parameter, nearby units are more related to each other and hence share similar information compared to units that are far apart (Tobler 1979) especially so if the information is spatially correlated. To capture the spatial (longitude/latitude) distribution of wet and dry nutrient deposits while avoiding duplicating neighboring information, the study area was stratified into three longitudinal zones and five latitudinal zones (Figure 2.1). Data collected from any point within a stratum were deemed a representative of that stratum and different from data collected from any other strata. Figure 2.1 also shows the geographic locations of the 15 sites where samplers were mounted. There were three replications of each sampling setup per site.

5.2.3 Monitoring, sampling and laboratory analyses

Distilled water (1/3 basin full, and with 1 drop of concentrated HCl to reduce biological activity) was used to trap the dry atmospheric deposits. Use of distilled water for trapping dry depositions may result in an overestimation of the actual deposited nutrients, as any deposited material cannot roll nor redeposit to another site as happens in natural soil systems. This procedure gives an indication of nutrient flow in the atmosphere rather than true nutrient deposition. Nutrient deposition should be measured by considering the seasonal increases in depth due to total accumulated material on the soil surface over a given period. However, because the dry-season depositions are low in quantity, and the depth of total accumulated dry season deposition is relatively small and difficult to capture accurately on soils for the relatively short duration of the research. The water-filled basin method was thus adopted as a proxy to estimate the maximum possible nutrient deposition. This method also gives a precise estimation of dry nutrient input in water bodies.

Top up was done every 3 days by carefully washing the surface of the trapping mesh with distilled water into the collecting samplers. This way, the 6-mm surface mesh always had free passage for dust collection. The water-filled basin method of trapping dust has been frequently used in sampling dust deposition (Lyngsie et al. 2011; Breuning-Madsen et al. 2012).

People were employed at each site during the sampling period and manually opened and closed simultaneously the wet and dry samplers when there were rains, and then closed and opened them 30 minutes after the rain. The bulk nutrient deposition sampler of each setup was, however, kept open throughout each month. This resulted in an observed microbial activity in the bulk sampler compared to the dry and wet samplers. Microbial activities were reduced to minimum by replacing the bulk deposition samplers with new ones at the end of each month. The relative levels of water collected in the bulk and wet sampler were used to assess the accuracy of timing for opening the wet deposition samplers (~99.9%: 100% score when height of bulk deposition < height of wet deposition due to evaporation in the bulk deposition setup).

To achieve a high degree of accuracy in sampler timing, the deposition samplers were mounted within 10 m perimeter of the sleeping places of the assistants (to ease night monitoring), and also under the condition that there were always two or more people available to attend to the samplers at any time during the study period. Unannounced control visits to the sampling sites were carried out during the sampling period to confirm that the conditions above were always satisfied.

Samples were collected at the end of each month and analyzed for nitrate-N, P, K, Ca, Mg and Na at the laboratory of Water Research Institute, Tamale.

5.2.4 Chemical analyses

Dry depositions were quantified by first evaporating the dust-trapping water to get the total dry deposits before extracting the various elements for analysis. Because the collected dry deposits consisted of samples from a mixture of sources (e.g., burned debris, dust particles), a total non-silicate bound elemental analysis was carried out. This was aimed at digesting the nutrients deposited by burned plant debris, and total non-silicate bound dust nutrients consisting of plant-available nutrients and unavailable but non-silicate bound elements. Andersen and Kisser (2004) noted that the composition of soils derived from either partial or total digestion is hardly relevant, as the fraction which even under extreme environmental conditions will be brought into solution (and made available for plants) is several orders of magnitude lower. Soil test extractants for P and the cations (Ca, Mg and K) were designed to rapidly assess the available nutrient status of dry deposit samples.

The problem, however, was that only limited amounts of dry deposits per site could be collected so that individual extractions for the respective elements could not be used. The use of a single extractant as an alternative was complicated by the nature of anticipated sources of nutrient inputs. The high Al/Fe oxide contents of surrounding soils, coupled with anticipated depositions of burned debris and some organic matter which in turn may affect the quantity, intensity and capacities of the individual nutrient supply. An analytical procedure was designed to dissolve and/or desorb the nutrients into solution and thus provide an index of the capacity to supply the elements to plants. To do this, samples were given two consecutive treatments:

i. Three distilled deionized water treatments with a mass (g) to liquid (cm^{-3}) ratio of 1:10 on a reciprocating shaker with a contact time of 30 minutes. Supernatants were decanted into the same volumetric flask. The water treatment was directly followed by:

ii. Six times HOAc (6 M) treatments with the same HOAc mass:volume treatment as in the water treatment step but at 1 hour reciprocating contact time each. This procedure is a modification of the Morgan procedure (Wolf and Beegle 2005), but with an extended contact time during reciprocating shaking (1 hour) and multiple extractions (6 times) to ensure that most non-silicate bound elements are extracted into solution.

In other non-silicate digestions involving harmattan-dusts across West Africa, Breuning-Madsen et al. (2012) used a 6N H_2SO_4 solution in their digestion, similar to Chineke and Chimeka (2009).

To ensure comparability with nutrient supply of soils, similar treatments as given to the dry deposited samples were given to soil samples collected at the same sites of dry deposit collection. Extracts were then analyzed for the elements. Wet depositions were, however, directly analyzed for the various elements: Nitrate-N and P by spectrophotometry (Moorcroft et al. 2001; Narayana and Sunil 2009; Kuo 1996), Ca and Mg by the ethylenediamine tetraacetic acid complexometric titration method, and Na and K by flame photometry. Ammonium and nitrate are the two inorganic N products of combustion (Certini 2005). However, ammonium is not stable and converts to nitrate in the biochemical process of nitrification few weeks after combustion (Covington and Sackett 1992). There was a time lapse of about 2 months between dust collection and laboratory analyses. For this reason and given that the quantity of dry dust collected was low, and both nitrate-N and ammonium-N could not be analyzed from the same sample, nitrate-N other than ammonium-N was analyzed.

5.2.5 Bulk nutrient deposit and net nutrient balance

Bulk nutrient deposition was estimated as the sum of wet and dry nutrient deposits. The annual nutrient balance across the northern region of Ghana was then estimated as the difference between the fire-induced elemental transfers (section 4.3.6) and the annual bulk nutrient deposits.

5.2.6 Statistical analyses

Values are reported as mean ± standard error of mean when statistical comparisons were made, or the 95% confidence interval of mean for all estimated values. Statistical differences in means of three or more groups (example: dry nutrient deposition by month) were analyzed by the analyses of variance technique while the difference between two groups (example: nutrient deposition by wet and by dry means) were analyzed using the pair-wise t-testing procedure, both at an alpha level of 0.05. Post hoc tests were run with the Duncan's multiple range test to determine the direction of variation and which classes differed. This post hoc test was used because the parameters being compared are not factorial in nature and do not correspond to several levels of a continuous variable. Temporal and geospatial linear relations in nutrient concentrations and depositions were analyzed using Spearman's correlation. Linear regressions were used to predict the linear relation between variables that had statistically significant correlations.

5.3 Results and discussion

5.3.1 Nutrient concentration in dry depositions across the northern region of Ghana

Estimated average dust fall rate across the northern region of Ghana during the harmattan season was 0.4-1g m^{-2} day^{-1}. This value is higher than the 0.25 g m^{-2} day^{-1} reported by Lyngsie et al. (2011) at Nyamkpala, and is attributed to the variations in geospatial dust fall rate across the study area. Appendices 9 and 10 provide chemical and physical properties of the soils across the sites where the deposition samples were collection. Figure 5.3 is a summary distribution of the monthly nutrient concentrations in dry deposits collected during the 2010/2011 fire/dry season. Dust nutrient concentrations from other studies are provide in Appendix 9 for comparison. The concentration of individual nutrients varied from one month to another (Figure 5.3). Besides N which showed significant ($P < 0.01$) differences in inter-monthly mean concentrations in the order November > December > January > February, there were no significant differences ($P > 0.05$) in mean nutrient concentrations between the four months of sample collection for all other nutrients. Mean (± standard error) nitrate concentrations, ranging from 110±10 mg kg $^{-1}$ in February to 2800±750 mg kg $^{-1}$ in November constitute a nitrate-N concentration of 24±3 mg kg $^{-1}$ and 640±170 mg kg $^{-1}$, respectively. Mean soil total N of 710 mg kg^{-1} (0.07%) estimated for the same sites of sample collection (Appendix 9) are about 1-38 times the nitrate-N concentration in the dry deposits.

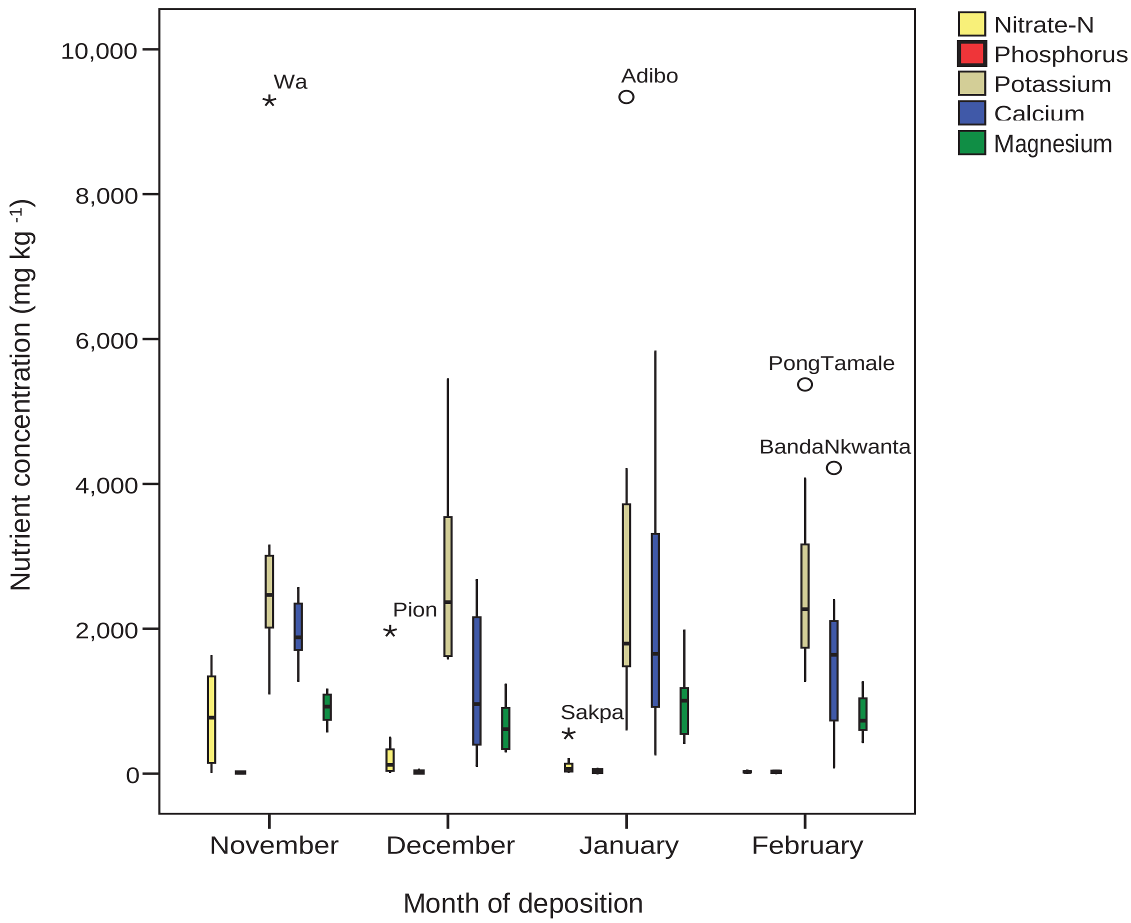

Figure 5.3 Distribution of monthly nutrient concentrations of dry deposits across the northern region of Ghana during the 2010-2011 fire/dry season. N = 15 for all nutrients except Na where n = 11 due to extreme values recorded in all months for the sites Wa, Nasia, Katani and Pong Tamale

The dry-deposited N concentration was lower than the ash N concentration of burned vegetation across the area in the same year (Table 4.7). Inter-monthly mean phosphate concentrations of 70±7 mg kg $^{-1}$ to 170±70 mg kg $^{-1}$ are comparable to the annual mean concentration estimates of 130 mg kg $^{-1}$ recorded by Breuning-Madsen et al. (2012) at a single location within the study area (Tamale). The estimated phosphate (PO_4^{-3}) concentration amounts to dry elemental P concentration of 23±2 mg kg $^{-1}$ to 56±24 mg kg $^{-1}$ and is 2-7 times the mean soil available P concentration of 14 mg kg $^{-1}$ (Appendix 9).

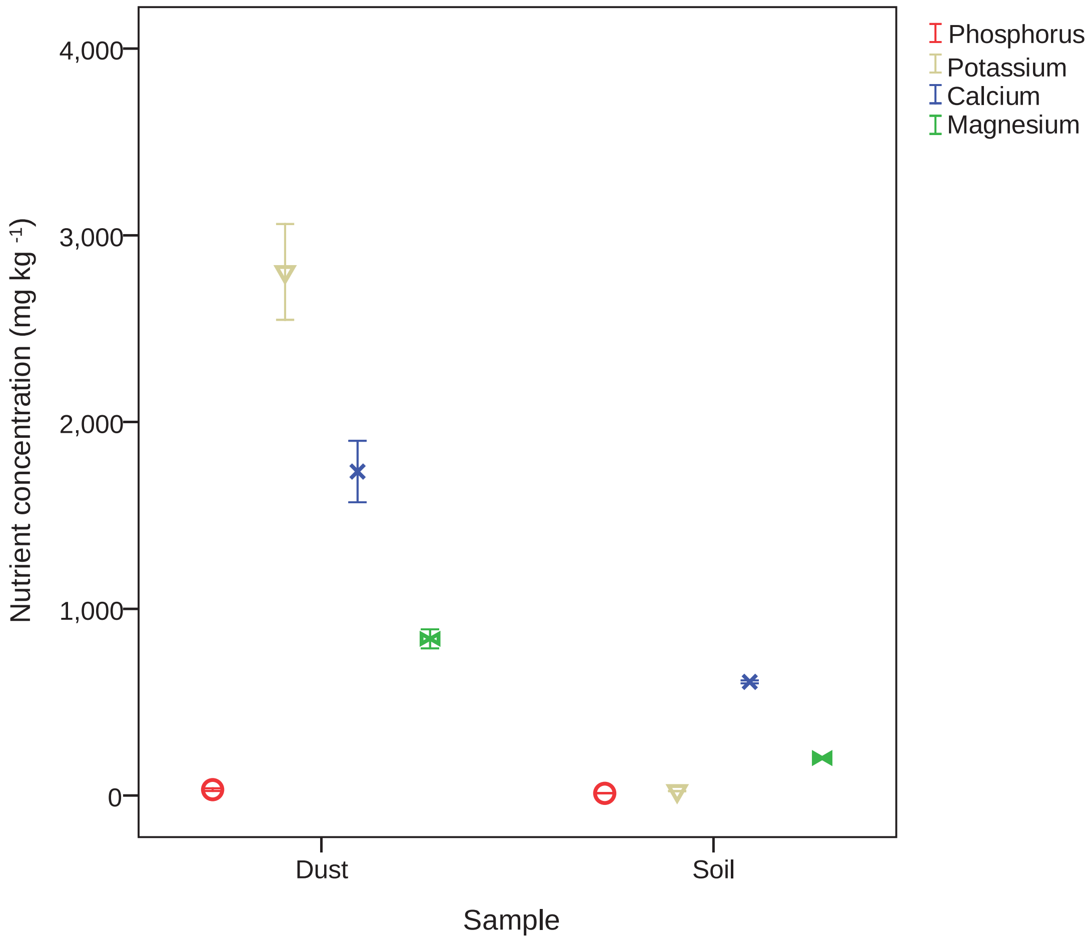

Figure 5.4 Comparative nutrient concentrations of dry atmospheric deposits and of soils collected at sites of the dry deposition during the 2010-2011 harmattan dry season across the northern region of Ghana. Samples given the same treatment: n = 59. Values are means, error bars are ±1 standard error of mean.

Annual dry deposition P concentration (31±7 mg kg^{-1}) was significantly higher than the soil P concentration (12±0.3) extracted the same way t (59) = 2.8, P = 0.01 (Figure 5.4). The dry P concentration was, however, lower than the 900 to 6000 mg kg $^{-1}$ estimated in burned ash across the area (Table 4.9). Mean monthly K concentration ranged from 2720±350 mg kg $^{-1}$ to 4150±1500 mg kg^{-1} and are also multiples (80-335) of the soil exchangeable K (24±2 mg kg $^{-1}$) with higher annual dry dust K concentration (3150±380) than the prevailing soil K concentration (25±0.9) under similar treatments t (59) = 8.3, $P < 0.01$. Mean monthly Ca (1680±280 to 2010±390 mg kg $^{-1}$) and Mg (740±90 to 930±120 mg kg $^{-1}$) concentrations across the 15 sites were higher than mean Ca (1180±290 mg kg $^{-1}$) and Mg (200±60 mg kg $^{-1}$) concentrations estimated at the single location within the study area (Breuning-Madsen et al. 2012). This high relative Ca and Mg concentration is attributed to the wider geographic space of sampling compared to the values from the single location. The Ca and Mg concentrations are multiples of the mean available soil Ca and Mg sampled at same geographic sites and extracted similarly (Figure 5.4) but lower than Ca (4000-12000 mg kg $^{-1}$) and Mg (1200-4700 mg kg $^{-1}$) concentrations of burned ash across the study area (Table 4.10)

The mean concentration of Na in the monthly dry deposits was 6371 mg kg $^{-1}$. This is excluding extreme Na concentrations of 36-80 g kg $^{-1}$ observed at the 4 northmost sites (Wa, Nasia, Katani, and Piong), which were higher than reported values in the literature (Appendix 9). Reasons for the high Na depositions at these sites could also not be readily ascertained. However, it is suggested to be linked to ocean sources and to the initial conditions that resulted in differences in their deposition at the different sites. Given the relatively low exchangeable soil Na across the sites (Figure 5.4 and Appendix 9), the observed high Na concentration may not be an annual phenomenon, otherwise, there should be a relatively high accumulation of Na salts or high exchangeable Na in the prevailing soil, which is not the case.

Contrary to the results of Chineke and Chiemeka (2009), who observed high Ca concentrations in harmattan-dust across Nigeria of magnitude ~21 times the concentration of K, this study shows that K concentration in the dry deposits across the northern region of Ghana was consistently higher than the Ca concentration (Figure 5.3). Elemental concentrations then followed the order Ca>Mg>nitrate-N>P as observed by Breuning-Madsen et al. 2012 (excluding N).

Unlike the soil-available nutrients, which did not show any wide variation or peculiar outliers in nutrient concentration, dry deposits showed wide variations in elemental concentration. In November depositions, for instance, extreme values of up to ~9290 g kg $^{-1}$ were recorded for K at Wa. Similar observations were recorded for K at Adibo in January and at Pong Tamale in December. Similar instances of isolated high concentrated elements are shown in Figure 5.3. The comparatively wide variations in dry deposit nutrient concentrations across the various sites suggest wide variations in the sources of these nutrients. The high elemental concentrations suggests other sources for the elements than harmattan-dust. In this sense, particulate entities from incomplete vegetation combustion may contribute to the observed high nutrient concentrations. Concentrations of all the elements (N, P, K, Ca, Mg) in the dry depositions were consistently lower than the corresponding concentrations in ash of burned vegetation across the study area (Table 4.7, Table 4.9 and Table 4.10). This suggests the return of a mixture of fire-induced particulate transferred elements coupled with low-nutrient source materials (probably external harmattan-dust) into the system. Though this high nutrient-concentrated materials is added to the soil, the net supply to the soil's available pool is minimal, given the relatively low amounts of total dry depositions per unit area (53 ~122 Mg km^{-2}).

5.3.2 Spatio-temporal determinants of dry deposits across the northern region of Ghana

Longitudinal and latitudinal position and month of deposition affect the concentration of deposited nutrients, the amount of dust deposited and the quantity of nutrients deposited at a given location (Table 5.2). The higher the partial eta square value (ηp^2), the greater the impact of a given parameter on the measured variable, independent on the significance level. The month of deposition had higher influence on the concentration of dry deposits than the geospatial location of sample collection. Within the same month, however, latitudinal position of sampling had a greater influence on the concentration of N, P, K, Ca and Mg than the longitudinal position.

Latitude is a greater geospatial predictor of dust amount and the quantity of deposited dry nutrients (N, P, K, Ca, Mg, and Na) across the northern region of Ghana with more dust falling out closer to the source in the north. This observation confirms that of Anuforom (2007) for the Sahel region of Nigeria. Based on these results, the geospatio-temporal determinants of dry deposition across the northern region of Ghana are in the order latitudinal position > month of deposition > longitudinal position.

Table 5.2 Spatio-temporal determinants of dust amount (kg km^{-2}), dust nutrient concentration (mg kg^{-1}), and dust nutrient deposition (kg km^{-2}) across the northern region of Ghana during the 2010-2011 harmattan dry season. Values are partial eta square (ηp^2), level of significance in brackets.

	Dust	Nitrate	Phosphate	K	Ca	Mg	Na
Concentration (mg kg^{-1})							
Longitudinal block	---	0.03	0.55	0.15	*0.70	*0.72	0.52
	---	(0.91)	(0.10)	(0.62)	(0.02)	(0.02)	(0.11)
Latitudinal block	---	0.51	0.32	0.28	**0.63	0.36	**0.70
	---	(0.06)	(0.28)	(0.36)	(0.01)	(0.22)	(0.00)
Month	---	0.81	0.67	0.41	0.92	0.93	0.32
	---	(0.42)	(0.35)	(0.59)	(0.74)	(0.49)	(0.67)
Long. block *Lat block	---	0.24	0.37	0.39	0.29	0.37	0.45
	---	(0.52)	(0.21)	(0.11)	(0.35)	(0.15)	(0.06)
Long. block * Month	---	0.16	0.13	0.20	0.16	0.11	0.32
	---	(0.61)	(0.78)	(0.49)	(0.62)	(0.82)	(0.15)
Lat. Block * Month	---	0.28	0.42	0.35	0.20	0.33	0.27
	---	(0.69)	(0.31)	(0.46)	(0.91)	(0.61)	(0.73)
Deposition (kg km^{-2})							
Longitudinal block	0.52	0.03	0.44	0.12	0.21	0.21	0.53
	(0.11)	(0.92)	(0.19)	(0.67)	(0.49)	(0.49)	(0.10)
Latitudinal block	**0.85	*0.51	0.45	0.47	**0.70	**0.73	**0.75
	(0.00)	(0.05)	(0.10)	(0.08)	(0.00)	(0.00)	(0.00)
Month	0.59	0.95	0.43	0.54	0.69	*0.79	0.42
	(0.06)	(0.47)	(0.20)	(0.44)	(0.17)	(0.04)	(0.35)
Lon.g block *Lat block	0.34	0.21	0.40	0.29	0.30	0.37	*0.51
	(0.21)	(0.65)	(0.15)	(0.34)	(0.31)	(0.15)	(0.02)
Lon.g block * Month	*0.43	0.15	0.11	0.23	0.29	0.21	0.36
	(0.03)	(0.65)	(0.84)	(0.36)	(0.21)	(0.43)	(0.09)
Lat. Block * Month	0.48	0.24	**0.67	0.31	**0.31	0.40	0.37
	(0.12)	(0.82)	(0.01)	(0.61)	(0.60)	(0.29)	(0.38)

*N = 60. *Significant effect at 0.05. **Significant effect at 0.01, Long. = longitudinal, Lat. = latitudinal, --- = same as deposition*

To determine the linear relation and direction of impact of the spatio-temporal variables, Pearson's correlation between the nutrient variable (concentration, deposition) and the spatio-temporal variables were computed, after which the exact linear relations between statistically significantly (P < 0.05) correlated parameters were modeled by a simple linear regression.

5.3.3 Spatial distribution of dry depositions across the northern region of Ghana

The nature of the effect of latitude and longitude on dust deposition, dust nutrient concentration and dust nutrient deposition is provided in Table 5.3. The table also shows the inter-nutrient linear relations in the dry deposits. Table 5.4 shows the significant ($P < 0.05$) linear relations for monthly inter-nutrient concentrations across the northern region of Ghana based on significant correlations from Table 5.3 (see Appendices 11 and 12 for the monthly inter-nutrient correlations). Table 5.5 shows the significant ($P < 0.05$) linear relations for the spatio-temporal deposition of dust, spatial (longitude, latitude) distribution of total annual nutrient deposits, and the relation between dust amount and nutrient deposit during the sampling period.

Quantity of dust deposits positively correlates (Pearson's correlation coefficient $c = 0.66$, $P < 0.001$) with latitude of dust deposition, while the correlation with longitude is insignificant ($c = 0.22$, $P = 0.09$). The spatial distribution of dust confirms the study by He et al. (2007) and Chester et al. (1972), who independently reported a decline in dust amount towards the equator. Potassium, Na and phosphate concentrations increase with increasing latitude while Mg, Ca and nitrate concentrations decrease with increasing latitude. The sources of dry nutrients during the harmattan season vary from harmattan-dust resuspension (Stoorvogel et al. 1997), redistribution of local dusts at short distances from their source of origin (He et al. 2007; Lyngsie et al. 2011), to the redistribution of burned debris (section 4.3.6). The positive inter-nutrient concentration correlation between Ca and Mg ($c = 0.77$, $P < 0.01$) suggests a potentially common source for these nutrient elements. Similarly, the positive inter-nutrient concentration correlation between K and Na ($c = 0.31$, $P < 0.05$) suggests a closely linked source for K and Na.

Table 5.3 Pearson's correlation matrix for spatial distribution of dry atmospheric deposition (kg km^{-2}) and nutrient concentration (mg kg^{-1}) across the northern region of Ghana during the 2010-2011 harmattan dry season. Values are coefficients, significant level (two-tail) in brackets.

	Ca	Mg	K	Na	Nitrate	Phosphate	Longitude	Latitude
[1]Monthly concentration (mg kg^{-1})								
Dust amount	-0.26	-0.21	-0.045	**0.40	-0.22	0.13	0.22	**0.66
	(0.05)	(0.11)	(0.72)	(0.00)	(0.13)	(0.32)	(0.09)	(0.00)
Ca	1	**0.77	-0.05	*-0.31	0.01	0.03	-0.24	-0.15
		(0.00)	(0.73)	(0.05)	(0.97)	(0.83)	(0.06)	(0.27)
Mg		1	-0.08	-0.18	-0.03	0.02	-0.22	-0.10
			(0.55)	(0.27)	(0.82)	(0.99)	(0.09)	(0.44)
K			1	*0.31	0.08	0.10	0.07	0.12
				(0.05)	(0.58)	(0.47)	(0.61)	(0.35)
[3]Na				1	-0.17	-0.05	*0.30	0.14
					(0.34)	(0.70)	(0.02)	(0.39)
Nitrate					1	-0.03	0.08	-0.12
						(0.86)	(0.58)	(0.40)
Phosphate						1	-0.20	*0.23
							(0.15)	(0.04)
[1]Monthly deposition (kg km^{-2})								
Dust	**0.48	**0.79	*0.26	**0.71	0.12	**0.45	0.22	**0.66
	(0.00)	(0.00)	(0.05)	(0.00)	(0.39)	(0.00)	(0.10)	(0.00)
Ca	1	**0.85	**0.48	0.22	*0.31	0.22	-0.08	**0.39
		(0.00)	(0.00)	(0.10)	(0.02)	(0.10)	(0.55)	(0.00)
Mg		1	**0.32	**0.46	0.15	**0.38	0.06	**0.57
			(0.01)	(0.00)	(0.24)	(0.00)	(0.67)	(0.00)
K			1	0.24	**0.55	0.21	0.08	**0.33
				(0.07)	(0.00)	(0.12)	(0.57)	(0.01)
[3]Na				1	**0.41	0.20	*0.28	**0.71
					(0.01)	(0.12)	(0.04)	(0.00)
Nitrate					1	**0.59	0.01	0.12
						(0.00)	(0.97)	(0.39)
Phosphate						1	-0.15	**0.43
							(0.29)	(0.00)
[2]Total annual deposition (kg 0.01 km^{-2})								
Dust	0.50	**0.95	0.45	**0.89	0.32	*0.53	0.27	**0.85
	(0.06)	(0.00)	(0.09)	(0.00)	(0.25)	(0.04)	(0.33)	(0.00)
Ca	1	**0.86	*0.60	0.30	0.47	0.33	-0.13	**0.62
		(0.00)	(0.01)	(0.28)	(0.08)	(0.23)	(0.64)	(0.01)
Mg		1	*0.55	**0.65	0.37	0.48	0.08	**0.83
			(0.03)	(0.01)	(0.18)	(0.07)	(0.79)	(0.00)
K			1	0.29	*0.61	0.48	0.13	*0.59
				(0.30)	(0.02)	(0.07)	(0.64)	(0.02)
[4]Na				1	0.35	0.29	0.36	**0.67
					(0.2)	(0.29)	(0.19)	(0.01)
Nitrate					1	0.42	0.01	0.44
						(0.12)	(0.98)	(0.10)
Phosphate						1	-0.26	**0.69
							(0.35)	(0.01)

*[1] n = 60, [2]n = 15, [3]n = 44, [4]n = 11, * significant correlation at 0.05, **significant correlation at 0.01*

Table 5.4 Linear regressions and model fit parameters for statistically correlated ($P < 0.05$) dry nutrient concentrations (mg kg^{-1}) across the northern region of Ghana during the 2010 -2011 harmattan dry season

Month	Relation	R	R^2	SEE	Sig. level
	[1]General				
D vs Na	D = 0.008Na + (109)	0.41	0.17	130	<0.001
Na vs K	Na = 1.33K + (3041)	0.31	0.10	6963	0.051
Ca vs Mg	Ca = 2.714Mg - (426)	0.77	0.59	828	<0.001
	November				
Ca vs Mg	Ca = 2.712Mg -(414)	0.86	0.74	583	<0.001
Na vs Ca	Na = 0.151Ca + (1615)	0.71	0.51	882	0.032
Mg vs Phosphate	Mg = 1471* (-13.4phosphate)	0.62	0.39	288	0.040
	December				
Ca vs Mg	Ca = 2.269Mg + (48)	0.55	0.30	1252	0.031
Na vs Ca	Na = -5Ca + (14554)	0.70	0.49	5246	0.043
K vs Na	Na = 3.6K - (2709)	0.84	0.70	4038	0.011
Nitrate vs phosphate	Nitrate = 34.7phosphate - (1128)	0.63	0.39	2162	0.051
	January				
Ca vs Mg	Ca = 2.9Mg - (675)	0.89	0.79	719	<0.001
	February				
D vs Mg	D = -0.48Mg + (649)	0.69	0.47	141	<0.001
D vs Ca	D = -0.098Ca + (429)	0.58	0.33	159	0.032
D vs Na	D = 0.017Na + (83)	0.81	0.66	113	<0.001
Na vs Ca	Na = -5Ca + (17876)	0.68	0.46	6993	0.021
Na vs Mg	Na = -27.7Mg + (32267)	0.79	0.63	5806	<0.001

N = 15, [1]n = 44, Inter-nutrient concentration relations not shown were not significant ($P > 0.05$), R = multiple correlation coefficient, R^2 = coefficient of determination, SEE = Standard error of the estimate. D = amount of dust deposited (kg 0.01km^{-2}), nitrate = NO_3^{-1}, phosphate = PO_4^{-3}. Monthly relations determined from significant correlations from values in Appendices 11 and 12.

The negative relations between Ca and Mg concentrations on the one hand with Na and K concentration on the other hand for all sites suggest that substantial amounts of deposited Na and K may not have come from same sources as Ca and Mg. Significant positive correlation of Na concentration with longitude contrary to the negative longitudinal effect on the concentration of Ca and Mg further suggest that most of the Na deposited across the region may have come from sources other than the sources of the other nutrients, and that it is closely associated with K. However, the observed high Na concentrations (section 5.3.1) suggest a potentially saline source for the deposited Na. As noted by Levin et al. (1996), dry dust is a coating surface for the Aeolian transfer of sea salts during transport.

Table 5.5 Linear regressions and model fit parameters for statistically correlated (*P* < 0.05) spatio-temporal dry nutrient deposition across the northern region of Ghana during the 2010 -2011 harmattan dry season. Linear regression modelled from total deposition correlations (Table 5.3) and monthly deposition correlations (Appendices 13 and 14).

	Month	Relation	R	R^2	SEE	Sig. level
Spatio-temporal distribution of harmattan-dust (kg 0.01 km^{-2})						
	January	D = (40Lat) + (57.4Long)	0.83	0.69	229	<0.001
	February	D = (39.7Lat) + (96Long)	0.90	0.81	151	<0.001
	November	D = (11.6Lat) + (5.3Long)	0.80	0.64	82	<0.001
	December	D = (28Lat) + (37Long)	0.84	0.71	155	<0.001
	Total annual	D = (850Lat) + (198Long) - 6500	0.91	0.83	268	<0.001
Spatial distribution of total annual dry nutrient deposition (kg 0.01km^{-2})						
	Total annual	Phos= (0.15Lat) –(Long0.026 Long)-1.237	0.72	0.51	0.09	0.013
	Total annual	K = (3.7Lat) + (0.633Long) –29	0.62	0.38	3	0.051
	Total annual	Ca= (0.864Lat) –(0.073Long) - 6.7	0.62	0.39	0.74	0.051
	Total annual	Mg=(0.522Lat) + (0.052Long) – 4.13	0.84	0.71	0.22	<0.001
Dust deposition versus amount of nutrient deposited (kg 0.01km^{-2})						
Ca	January	Ca=0.124(D/100)	0.34	0.12	0.43	0.214
	February	Ca=0.095(D/100)	0.27	0.08	0.23	0.332
	November	Ca=0.162(D/100)	0.92	0.84	0.09	<0.001
	December	Ca=0.158(D/100)	0.76	0.58	0.37	<0.001
Mg	January	Mg=0.069(D/100)	0.91	0.82	0.13	<0.001
	February	Mg=0.059(D/100)	0.96	0.91	0.06	<0.001
	November	Mg=0.070(D/100)	0.97	0.93	0.02	<0.001
	December	Mg=0.077(D/100)	0.89	0.79	0.11	<0.001
	Total annual	Mg=0.068 (D/100)	0.95	0.90	0.24	<0.001
K	January	K=0.241(D/100)	0.82	0.67	0.66	<0.001
	February	K=0.253(D/100)	0.95	0.90	0.28	<0.001
	November	K=0.468(D/100)	0.84	0.71	0.39	<0.001
P	January	Phosphate=0.019(D/100)	0.67	0.45	0.08	0.012
	February	Phosphate=0.006(D/100)	0.89	0.79	0.78	<0.001
	November	Phosphate=0.006(D/100)	0.92	0.86	0.00	<0.001
	December	Phosphate=0.010(D/100)	0.28	0.08	0.03	0.343
	Total annual	Phosphate=0.012(D/100)	0.75	0.56	0.11	<0.001

N = 15, Relations not shown were not significant (P > 0.05 level). R = multiple correlation coefficient, R^2= coefficient of determination, SEE = Standard error of the estimate. D = amount of dust deposited (kg 0.01 km^{-2}), Lat = Latitudinal position (degrees), Long = longitudinal position (degrees), phos = phosphate (PO_4^{-3})

Lyngsie et al. (2011) reported similar saline environmental sources for components of harmattan-dust when their findings revealed traces of pirssonite and the tectosilicatic zeolite analclime (both of which precipitate in saline environments) in the crystal morphology of harmattan-dust. Because the diffractive properties of the deposited samples were not checked (due to limited sample amount), the observation by Lyngsie et al. (2011) could not be confirmed.

However, unlike Ca and Mg concentrations, the correlation between K concentration and longitudinal position was not negative but positive and insignificant. This also applied to its correlation with latitude compared to Ca and Mg, indicating a close association of K sources with Na sources. However, the concentration of phosphate in the dry deposits, like Na concentration, increased significantly with increasing latitude (c = 0.23, P = 0.04). The negative inter-nutrient concentration correlation between Na and phosphate, however, suggests differences in the main sources of these two nutrients. P is likely redistributed in particulate forms after burns.

The quantity of monthly dust deposits and that of monthly nutrient deposits increased with increasing latitudinal position of dust collection (also see Appendices 11, 12 and 13). Dust increment with latitude is attributed to distance to the Saharan dust sources. All things being equal, particles transported in the harmattan wind may deposit closer to the source of origin due to the influence of gravity. The higher the latitude of deposition, the shorter the distance to the main dust sources and, consequently, the higher the dry deposition. In this light, it can be expected that most dry depositions at higher latitudes are from external sources, while depositions at lower latitudes may be from local redistribution.

The increase in nutrient deposition with latitude is attributed to the increasing dust deposition with increasing latitude. This observation also confirms that of Anurofom (2007) and suggests similar spatial trends in dry deposition between the northern region of Ghana and the Sahel region of Nigeria, which is attributed to same source for the bulk of dry depositional materials. The bulk of the dry depositions is attributed to the dust-laden north-easterly harmattan wind coming from the Bodélé region of Bilma and Faya-largeau in the Sahelian Chad Basin (Kalu 1979; Tiessen et al. 1991; Brooks and Legrand 2000; Goudie and Middleton 2001), from the Tibesti mountains of Niger (Kalu 1979), parts of Mali, Algeria, Mauritania, southern Egypt, and northern Sudan (Brooks and Legrand 2000) through Aeolian activities. Except Na deposition, which showed significant positive correlation with the longitudinal position of sampling (c = 0.28, P = 0.04), deposition of all other nutrients showed no significant (P > 0.05) correlation with the longitudinal position of dust collection. The higher the quantity of dust deposited, the higher the amount of all plant nutrients deposited. There is a positive inter-nutrient deposition correlation between all plant nutrients in the dry deposition.

As in the monthly depositions, total annual dust deposition and plant nutrient deposits positively correlate with the latitudinal position of dust collection, while they do not significantly ($P > 0.05$) correlate with the longitudinal position. Positive total annual inter-nutrient deposition correlations exist between all nutrients. The results discussed above confirm that latitude has a stronger geospatial influence on the amount of dust and dust nutrients deposited across the northern region of Ghana than longitude.

5.3.4 Temporal distribution of dry depositions across the northern region of Ghana

Table 5.6 shows the monthly and total annual dry depositions across the northern region of Ghana during the 2010/2011 harmattan dry season. Significant ($P < 0.05$) differences exist in the amount of dust, phosphate and Mg deposited over the four months (November, December, January, and February), while no significant ($P > 0.05$) differences exist in the quantities of nitrate-N, K, Ca and Na deposited in these months. A total mass of 53-122 Mg km^{-2} $year^{-1}$ was deposited in dry deposits across the northern region of Ghana during the dry season. The total annual dry deposits quantified in this study are comparable to those of Orange et al. (1993) and McTainsh (1980), who estimated annual dust deposits across the West African region to be about 36.5-200 Mg km^{-2} $year^{-1}$ and across northern Nigeria to be about 99 Mg km^{-2} $year^{-1}$. The estimated value is also comparable to values of 42 ± 34 Mg km^{-2} estimated across the northern region of Ghana by Breuning-Madsen and Awadzi (2005). The amount is, however, higher than the 28 Mg km^{-2} estimated by Lyngsie et al. (2011) at a single location (Nyamkpala) in the northern region of Ghana. Single location sampling does not cover the geospatial variations in the quantity of dry depositions, since site-specific total annual dust amounts estimated across the 15 sites in this study also capture the single site value by Lyngsie et al. (2011), and ranged from 12-202 Mg km^{-2} depending on the geographic location of sampling.

Table 5.6 Monthly total annual dry depositions (Mg km^{-2}) and the corresponding dry elemental nutrient deposits (kg km^{-2}) across the northern region of Ghana during the 2010-2011 harmattan dry season. Values are 95% confidence interval of mean, mean in brackets.

	January		February		November		December		Sig. level	Total deposit		% deposition	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper		Lower	Upper	Lower	Upper
*D	18	41	17	38	6	13	13	30		53	122	100	100
	(30 [a])		(26 [a])		(10 [c])		(21[ab])		0.03				
N	0.3	9	0.3	1.2	2	13	0.5	19		3	42	0.005	0.034
	(3.6)		(0.9)		(6.6)		(6.2)		0.25				
*P	0.1	3.8	0.4	0.8	0.1	0.3	0.1	1.5		0.7	6.3	0.001	0.005
	(2 [a])		(0.7 [b])		(0.3 [b])		(1 [ab])		0.05				
K	46	128	44	100	11	78	0	312		100	618	0.190	0.508
	(90)		(72)		(44)		(144)		0.41				
Ca	27	72	23	43	7	26	11	60		70	200	0.128	0.165
	(50)		(33)		(16)		(35)		0.07				
**Mg	15	33	13	23	4	11	7	26		40	90	0.073	0.076
	(24 [a])		(18 [a])		(7 [b])		(16 [ab])		0.01				
[1]Na	59	205	21	267	1	37	5	315		90	820	0.162	0.677
	(132)		(144)		(20)		(160)		0.15				

*n = 15, [1]n = 11. *significant monthly variation at 0.05 level, **significant monthly variation at 0.01 level. [abcde] = Post hoc test of statistical difference according to Duncan's multiple range test at 0.05 significance level, lower = lower bound 95% confidence interval of mean, upper = upper bound 95% confidence interval of mean.*

Highest dry depositions occurred in January at 18-41 Mg km^{-2}, while lowest occurred in November at 6-13 Mg km^{-2}. Total deposition of plant nutrients during the dry season amounted to 3-42 kg km^{-2} nitrate-N, 0.7-6.3 P kg km^{-2}, 100-618 kg km^{-2} K, 60-200 kg km^{-2} Ca, 40-90 kg km^{-2} Mg, and 90-820 kg km^{-2} Na. These values are comparable to values estimated in the south-western Tai National Park of La Côte d'Ivoire with mean values of 11 kg km^{-2} P, 250 kg km^{-2} K, 350 kg km^{-2} Ca, and 40 kg km^{-2} Mg (Stoorvogel et al. 1997). The values are also comparable to those quantified at a single location (Nyamkpala) in the northern region of Ghana by Tiessen et al. (1991) at about 300 kg km^{-2} K, but less than the 400 kg km^{-2} Ca and 140 kg km^{-2} Mg estimated by Tiessen et al. (1991).

The estimated nutrients deposited by dry means across the northern region of Ghana during the harmattan season (Table 5.7) constitute about 1-19% N, 4-20% P and 110-680% K of the nutrient imports in the form of fertilizers into the whole of Ghana (see section 4.3.6). Dry nutrient deposition across the northern region of Ghana is therefore an economically important source of plant nutrient input for the country.

Table 5.7 Total annual dry and wet (bulk) atmospheric plant nutrient deposits (Gg) across the northern region of Ghana (70,383 km^2) during the 2010-2011 dry and wet seasons

	Dry		Wet		Bulk	
	lower	upper	lower	upper	lower	upper
N	0.2	3	2	8	2	11
P	0.1	0.5	0.2	1.6	0.3	2.1
K	7.1	43	13	61	38	91
Ca	4.9	14	113	282	120	290
Mg	2.8	6.3	84	183	88	190
Na	6.3	58	19	106	25	162

Lower = lower bound 95% confidence interval of mean, Upper = upper bound 95% confidence interval of mean, N = nitrate-N

5.3.5 Source of the high dry nutrient deposition

Stoorvogel et al. (1997) reported harmattan-dust to be the major source of plant nutrient deposits during the dry season. The Saharan Niger and Chad sources of harmattan-dust (Goudie and Middleton 2001) are regions with relatively low soil fertility status (Appendix 9), suggesting a source of origin other than harmattan-dust for the high nutrient depositions recorded. Redistribution of nutrients transferred into the atmosphere during vegetation burning might be a major source of the high atmospheric nutrient returns. The bulk of dry deposition occurs in the order January> February> December> November (Table 5.6). Differences in the order of mean monthly depositions for the various nutrients suggest three reasons for the source of the dry nutrients: 1) All nutrients are not from same source otherwise they would follow a trend similar to that of the total dust deposition, 2) the different sources of nutrients dominate deposition at different periods during the dry season, and 3) there is an influence of local redistribution either by burned particulate entities or by local soils.

Deposit of individual nutrients should follow similar temporal trends as those of dust deposition if the nutrients come from the same source. Nutrient concentration should be about same if the source is same while they should vary for different nutrient sources (burned debris, Aeolian transport from external sources, local dust redistribution). If the bulk of nutrients deposited in a given month is from different sources, then the concentration of the various nutrients in the different sources will be the predominant determining factor of the quantity of each nutrient deposited and not the total dust deposit collected in that month. In this case, the relative fraction of total dry deposits from the different nutrient sources will be the predictive factor for the quantity of each nutrient deposited in the given month. The period of dominance for the different sources of nutrients during the harmattan dry season defines the major nutrients that are deposited across the region in a given month. For instance, fire activity is highest during the last week of December (section 3.3.3). One would expect that redistribution of fire-transferred particulate elements (N, P, K, Ca, Mg and Na) and the debris from burned vegetation will contribute to high nutrient deposition between December and January. On the other hand, local dust redistribution and external aerosol deposits will be the major sources of nutrient deposits in early November and late February when there are relatively fewer fires. The varying nutrient concentrations and deposition with dust deposits suggest that harmattan-season dry-nutrient deposits across the northern region of Ghana have varied sources of origin, and that the dominant source at any time determines the quantity of each nutrient deposited across the region in a given month. The relatively high concentration of dry nutrient deposits (Figure 5.3) compared to the concentrations of nutrients in the soils across the study area (Figure 5.4) also shows that deposited dry nutrients might not be from the redistribution of local soils alone, or that Harmattan picks up the finer particles of soil that are richer in nutrients than the bulk soil. The concentration difference also suggests substantial amounts of dry nutrient deposits to be from the return of burned particulate plant debris.

5.3.6 Spatio-temporal distribution of wet depositions across the northern region of Ghana

Latitudinal position (ηp^2 = 0.42) and month (ηp^2 = 0.94) of collection determine the amount of rainfall across the northern region of Ghana (Table 5.8).

Table 5.8 Spatio-temporal determinants of rainfall amount ($m^3\ km^{-2}$), rainfall nutrient concentration ($mg\ l^{-1}$)), and rainfall nutrient deposition ($kg\ km^{-2}$) across the northern region of Ghana from July 2010 to June 2011. Values are partial eta square (ηp^2), level of significance in brackets.

	Rain volume $m^3\ km^{-2}$	Nitrate	Phosphate	K	Ca	Mg	Na
Nutrient concentration ($mg\ l^{-1}$)							
Longitudinal block	---	0.30	0.07	0.68	0.26	0.02	0.24
		(0.13)	(0.45)	(0.15)	(0.14)	(0.86)	(0.53)
Latitudinal block	---	0.14	0.07	0.37	*0.26	0.09	0.76
		(0.35)	(0.50)	(0.42)	(0.04)	(0.63)	(0.21)
Month	---	**0.84	**0.95	0.85	**0.80	*0.53	0.76
		(0.01)	(0.00)	(0.17)	(0.00)	(0.02)	(0.60)
Long. block *Lat block	---	0.16	0.07	0.49	0.25	0.29	0.51
		(0.70)	(0.56)	(0.76)	(0.19)	(0.16)	(0.55)
Long. block * Month	---	0.20	0.17	0.53	0.37	**0.63	0.28
		(0.76)	(0.67)	(0.44)	(0.11)	(0.00)	(0.63)
Lat. block * Month	---	0.40	0.29	0.73	0.54	**0.72	0.40
		(0.65)	(0.77)	(0.49)	(0.10)	(0.00)	(0.87)
Nutrient deposition ($kg\ km^{-2}$)							
Longitudinal block	0.06	0.11	0.10	0.09	*0.27	0.11	0.16
	(0.52)	(0.27)	(0.31)	(0.33)	(0.03)	(0.29)	(0.15)
Latitudinal block	**0.42	0.13	0.05	0.14	0.15	0.08	0.09
	(0.00)	(0.17)	(0.68)	(0.15)	(0.13)	(0.46)	(0.37)
Month	**0.94	0.98	0.99	**0.55	**0.80	**0.86	0.62
	(0.00)	(0.09)	(0.20)	(0.01)	(0.00)	(0.00)	(0.09)
Long. block *Lat. Block	*0.16	0.09	0.04	0.10	0.05	0.11	0.10
	(0.04)	(0.40)	(0.91)	(0.29)	(0.84)	(0.21)	(0.3)
Long. block * Month	**0.50	0.14	0.08	0.27	0.13	0.17	0.23
	(0.00)	(0.86)	(0.99)	(0.11)	(0.93)	(0.72)	(0.28)
Lat. block * Month	**0.53	0.24	0.28	**0.48	**0.61	**0.50	0.34
	(0.00)	(0.95)	(0.81)	(0.01)	(0.00)	(0.00)	(0.48)

**Significant effect at 0.05, **significant effect at 0.01, Lat. = latitude, Long = longitude, --- = same as deposition*

Month of rainfall is the greatest predictor of the quantity of rainfall collected in a given location, while longitudinal location has the least influence on the amount of rainfall. The nutrient concentration of wet depositions also depends more on the month than the geospatial location. Within the same month, latitude has a greater geospatial influence on the concentration of rainfall than longitude. The observation is the same for rainfall nutrient deposition.

In a given month, both latitude ($\eta p^2 = 0.53$) and longitude ($\eta p^2 = 0.50$) independently affect the quantity of rainfall with latitudinal position having a greater impact on amount of rainfall than longitudinal position. The interaction between latitude and longitude ($\eta p^2 = 0.16$) determines the quantity of rainfall across a geographic location in a given month. The difference between the total annual rainfall deposits and the inter-monthly geospatial predictors of rainfall suggests that though amount of rainfall at a given location in a given month may vary from that of another location, this variation may be compensated for by rainfall amounts in another month such that total annual rainfall may not vary much from one location to the other across the region.

5.3.7 Spatial distribution of wet depositions across the northern region of Ghana

Table 5.9 shows the Pearson's correlation coefficient for geospatial distribution of rainfall amount, monthly rainfall nutrient concentration, monthly wet nutrient deposition and geospatial distribution of total annual wet deposition across the northern region of Ghana. Table 5. 10 shows the corresponding linear relations for statistically significant ($P < 0.05$) rainfall deposition correlations from Table 5.9. The equations predict the geospatial distribution of monthly and total annual rainfall amount, and rainfall nutrient deposition across the northern region of Ghana. There was a general negative correlation between rainfall amount and rainfall nutrient concentration, i.e., the higher the rainfall amount, the lower the nutrient concentration for all nutrients except phosphate (PO_4^{-3}), which showed positive but insignificant correlation with rainfall amount suggesting a local source for phosphate deposition. With the exception of nitrate (NO_3^{-1}) and phosphate (PO_4^{-3}), significant positive inter-nutrient concentration correlations existed between Ca, Mg, K and Na.

Table 5.9 Pearson's correlation matrix for spatial distribution of rainfall amount (m^3 km^{-2}), rainfall nutrient concentrations ($mg\ l^{-1}$), and rainfall nutrient depositions ($kg\ km^{-2}$) across the northern region of Ghana from July 2010 to June 2011. Values are coefficients, significance level in brackets.

	Ca	Mg	K	Na	Nitrate	phosphate	Longitude	Latitude
				[1]Monthly concentration ($mg\ l^{-1}$)				
Rain vol	**-0.33	**-0.42	**-0.48	-0.18	-0.13	0.42	0.01	*-0.16
	(0.00)	(0.00)	(0.00)	(0.22)	(0.22)	(0.14)	(0.88)	(0.03)
Ca	1	**0.33	0.16	*0.32	0.03	0.51	0.01	-0.09
		(0.00)	(0.24)	(0.03)	(0.76)	(0.06)	(9.94)	(0.36)
Mg		1	**0.77	0.08	0.08	-0.45	-0.04	-0.09
			(0.00)	(0.62)	(0.45)	(0.10)	(0.72)	(0.36)
K			1	**0.44	-0.1	0.13	0.27	-0.21
				(0.00)	(0.5)	(0.84)	(0.05)	(0.13)
Na				1	0.02	NC	0.23	0.12
					(0.91)		(0.12)	(0.43)
Nitrate					1	-0.21	-0.01	0.07
						(0.73)	(0.91)	(0.52)
phosphate						1	0.07	-0.28
							(0.81)	(0.33)
				[2]Monthly deposition				
Rain vol	**0.46	**0.71	0.04	0.03	**0.24	*0.17	0.01	*-0.16
	(0.00)	(0.00)	(0.56)	(0.73)	(0.00)	(0.03)	(0.88)	(0.03)
Ca		**0.48	**0.40	**0.32	**0.29	0.06	-0.05	*-0.17
		(0.00)	(0.00)	(0.00)	(0.00)	(0.47)	(0.55)	(0.02)
Mg		1	**0.25	0.05	**0.37	0.10	-0.05	-0.08
			(0.00)	(0.54)	(0.00)	(0.17)	(0.49)	(0.26)
K			1	**0.55	0.04	-0.02	0.12	*-0.17
				(0.00)	(0.56)	(0.83)	(0.12)	(0.02)
Na				1	0.04	0.00	0.13	-0.01
					(0.61)	(0.97)	(0.08)	(0.92)
Nitrate					1	-0.01	-0.04	0.04
						(0.85)	(0.57)	(0.61)
Phosphate						1	0.05	-0.04
							(0.5)	(0.61)
				[3]Total annual deposition				
Rain vol	**0.74	0.40	0.39	0.45	0.16	0.24	0.00	**-0.88
	(0.00)	(0.14)	(0.15)	(0.1)	(0.58)	(0.38)	(0.99)	(0.00)
Ca	1	**0.65	0.07	0.14	-0.05	0.2	-0.25	**-0.75
		(0.01)	(0.82)	(0.63)	(0.87)	(0.48)	(0.38)	(0.00)
Mg		1	0.21	0.11	0.1	-0.1	-0.29	-0.36
			(0.44)	(0.7)	(0.73)	(0.74)	(0.29)	(0.19)
K			1	*0.62	0.24	0.03	0.44	-0.43
				(0.01)	(0.40)	(0.92)	(0.10)	(0.11)
Na				1	**0.66	-0.07	0.44	-0.28
					(0.01)	(0.82)	(0.1)	(0.32)
Nitrate					1	0.09	0.30	0.10
						(0.74)	(0.27)	(0.71)
Phosphate						1	0.16	-0.30
							(0.56)	(0.28)

*[1]n = 102, [2]n =180, [3]n =15, NC = not computed: P concentration below detectable limit; where P was detected, Na was below detectable limit, * significant correlation at 0.05, **significant correlation at 0.01, vol = volume.*

Table 5.10 Linear regressions and model fit parameters for statistically correlated (<0.05) spatio-temporal rainfall amount (m^3 0.01 km^{-2}) and rainfall nutrient deposition (kg 0.01 km^{-2}) across the northern region of Ghana from July 2010 to June 2011

Month	Relation	R	R^2	SEE	Sig. level
Spatio-temporal distribution of rainfall amount					
May	Vol = 4255-(309Lat.)-(332Long.)	0.76	0.6	353	0.012
June	Vol = 10911-(987Lat.)-(307Long.)	0.74	0.6	652	0.011
July	Vol = 5685-(391Lat.)+(47Long.)	0.79	0.6	211	<0.001
August	Vol = 13173-(1023Lat.)-(194Long.)	0.92	0.8	308	<0.001
September	Vol = 10566-(715Lat.)+(566Long.)	0.77	0.6	680	<0.001
October	Vol = 10360-(813.7Lat.)-(Long.121)	0.93	0.9	215	<0.001
Total annual	Vol = 56178-(4272Lat.)-(185Long.)	0.89	0.8	1503	<0.001
Monthly rainfall amount and Ca deposition					
April	Ca = 2.33(Vol/1000)+0.04	0.96	0.9	0.3	<0.001
May	Ca = 4.49(Vol/1000)-0.51	0.66	0.4	2.6	<0.001
June	Ca = 3.42(Vol/1000)+1.8	0.58	0.3	4.5	0.021
July	Ca = 1.28(Vol/1000)-1.911	0.81	0.7	0.3	<0.001
Monthly rainfall amount and Mg deposition					
April	Mg = 2.962(Vol/1000)-0.034	0.97	0.9	0.35	<0.001
May	Mg = 1.44(Vol/1000)-0.38	0.75	0.6	0.66	<0.001
June	Mg = 2.297 -0.68(Vol/1000)	0.62	0.4	0.79	0.014
Monthly Inter-nutrient depositions					
April	K = 0.825(Ca)	0.92	0.8	0.38	<0.001
	Na = 0.509(K)-0.138	0.76	0.6	0.43	<0.001
May	Na = 0.876(K)-0.28	0.8	0.6	0.69	<0.001
August	K = 0.111(Ca)-0.346	0.74	0.5	0.72	<0.001
October	K = 0.049(Ca)	0.63	0.4	0.15	0.013
Total annual wet nutrient deposition (kg 0.01 km^{-2})					
	Ca = 3(Vol/1000)-22.22	0.74	0.6	8.5	<0.001
	Ca = 164.9 -(15.1Lat.)-(3.6Long.)	0.81	0.7	7.7	<0.001
	Mg = 10.637 + 0.284(Ca)	0.65	0.4	4.1	0.014
	K = 0.501(Na) + 0.890	0.62	0.4	1.9	0.012
	Nitrate = 0.621(Na) + 0.937	0.66	0.4	2.1	0.011

n = 15, relations not shown were not significant (P > 0.05), R = multiple correlation coefficient, R^2 = coefficient of determination, SEE = Standard error of the estimate, vol = volume of rain (m^3 0.01 km^{-2} = 10000 mm), Lat. = Latitudinal position (degrees), Long. = Longitudinal position (degrees)

Unlike rainfall nutrient concentration, there was a positive correlation between rainfall amount and the quantity of nutrients deposited. Whereas positive and significant relations existed between amounts of Ca and Mg on the one hand and the amount of nitrate deposited on the other, the relation between amount of K and Na deposited with the amount of nitrate deposited was not significant. Also, phosphate deposition showed no significant (*P* > 0.05) relation with deposition of the other nutrients. The negative correlation between quantities of nutrients deposited by rain with latitude is a result of the decreasing rainfall amount with latitude.

Total annual rainfall amount negatively correlates (c = -0.88, P = 0.00) with the latitudinal position of rainfall collection but has no such correlation with longitude. Only total Ca deposition showed a significant positive relation with total annual rainfall amount.

Significant positive Ca-Mg concentration correlation (c = 0.33, $P < 0.001$), monthly deposition correlation (c = 0.48, $P < 0.001$), and total annual deposition correlation (c = 0.65, P = 0.01) strongly suggest a similar source for the bulk of Ca and Mg nutrients in wet deposition. Insignificant correlation of nitrate and phosphate concentrations with other nutrients suggests that the main fraction of these two species is sourced from an entirely different origin, probably from redistribution of nearby soils by wind prior to rainfall.

5.3.8 Temporal distribution of wet depositions across the northern region of Ghana

Temporal rainfall occurrence

Rainfall occurred all months except January (Figure 5.5). Rainfall occurrence across the 15 sites increased gradually from February onwards and was observed across all sites from May to October.

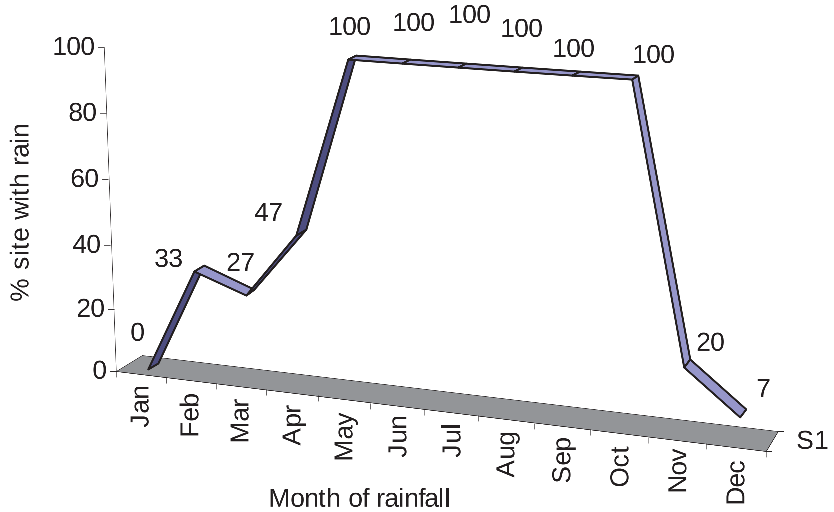

Figure 5.5 Monthly percentage number of sites with rainfall out of 15 geospatial rainfall sampling sites across the northern region of Ghana from June 2010 to July 2011

The number of sites that had rain reduced gradually from 15 sites in October to 3 sites (20%) in November. Only one site had rain in December. This observed trend follows a unimodal pattern of rainfall occurrence. The amount of rain increased sharply from 33±11 mm (mean±standard error of mean) in April to 173±13 mm in May and remained relatively stable at ~200 mm $month^{-1}$ in June and July (Figure 5.6). From July, the average monthly rainfall amount increased sharply to about twice the May-July amount, and reached a maximum at 388±18 mm in August after which it declined to 294±14 mm in October and finally to 12±8 mm in November.

Though all 15 sites recorded rains in May and August (Figure 5.5), the amount of rain in May (173±13 mm) was low compared to that in August (388 ±18 mm) when the highest rainfall occurred (Figure 5.6).

The unimodal pattern of rainfall occurrence across the northern region of Ghana can generally be grouped into two statistically significant periods based on rainfall amount. The mean May-July monthly rainfall amount (194±9 mm) was significantly less than that in August-October (339±12 mm). The estimated total annual rainfall across the northern region of Ghana (1670±77 mm) was higher than the mean annual rainfall amount of 1100 mm (Armah et al. 2010).

Temporal rainfall nutrient concentration and wet nutrient deposition

Rainfall nutrient concentration depends on the month of rainfall (Figure 5.6). With the exception of the Ca concentration, which did not follow similar trends in May and June, the nutrient concentrations for all nutrients were generally high in February when there were rainfall events, and gradually decreased through March and were lowest from July through to October when the rainfall amount was highest. November and December rains are generally associated with increasing nutrient concentrations. The observed monthly trend in rainfall nutrient concentration was due to the effects of dry atmospheric deposition and the atmospheric cleansing effect by rainfall at different time periods. In February, when only few sites recorded rainfall, suspended dust particles, burned debris and aerosol particles of the dry season are readily available in the atmosphere. Precipitation should, therefore, contain substantial amounts of nutrients dissolved from these sources at this time of the year.

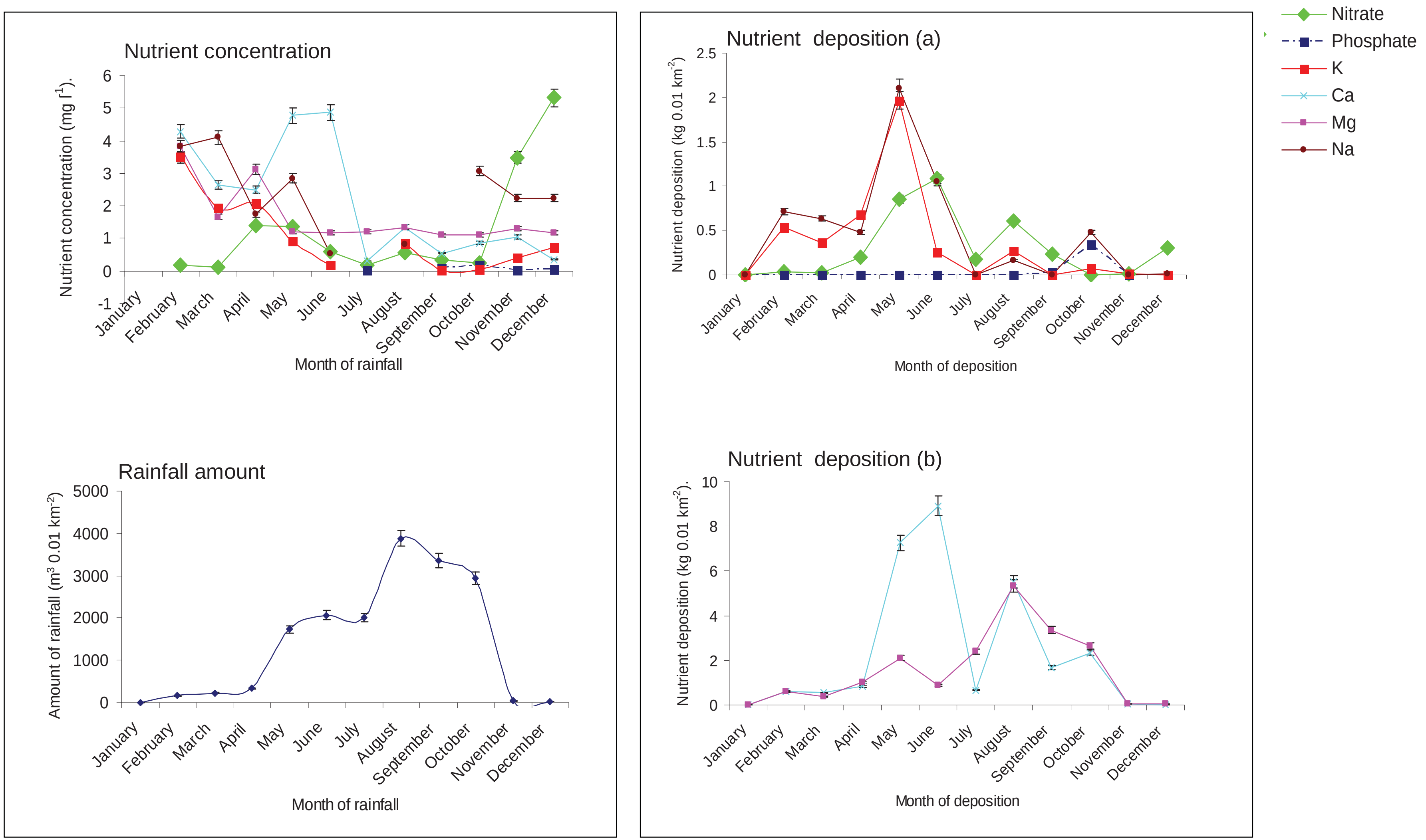

Figure 5.6 Monthly rainfall amount (m^3 0.01 km^{-2}), rainfall nutrient concentration (mg l^{-1}), and rainfall nutrient deposition (kg 0.01 km^{-2}) across the northern region of Ghana from July 2010 to June 2011. a = 0.5 kg steps, b = 2 kg steps, points are means, bars show 5% error.

The low amounts of rainfall in this time period also result in high nutrient concentrations. Subsequent rainfalls show reduced nutrient concentrations because of nutrient removal by preceding rains and a subsequent temporal dilution effect by increasing rainfall amount. From June through October, the high rainfall amounts result in the dilution of nutrient concentration. Furthermore, the atmosphere may not contain a large amount of nutrient suspensions during this period. These two factors resulted in the observed low nutrient concentration in the peak of the rainy season. In November/December (dry season) when burned debris and harmattan-dust nutrient suspensions are common in the atmosphere, rains around this time again result in high nutrient concentrations due to dissolution of materials from these sources.

Both rainfall amount and rainfall nutrient concentration are the determinants of wet nutrient deposition. Off-season nutrient concentration was highest for all nutrients: ranging from 9.3 mg l^{-1} in December to 0.11 mg l^{-1} in March for nitrate, 3.5 mg l^{-1} in February to 0.8 mg l^{-1} in December for K, 4.3 mg l^{-1} in February to 0.4 mg l^{-1} in December for Ca, 3.8 mg l^{-1} in February to 1.2 mg l^{-1} in December for Mg, and 4.7 mg l^{-1} in February to 2.2 mg l^{-1} in December for Na. The 95% confidence intervals for nutrient concentration during the rainy season of 0-3 mg l^{-1} for nitrate, 0.09-0.7 mg l^{-1} phosphate, 0-1.4 mg l^{-1} K, 0-6 mg l^{-1} Ca, 0.6-1.8 mg l^{-1} Mg and 0-7 mg l^{-1} Na were higher than those measured in other parts of the world (Emmerich 1990). The measured average (n = 90) rain-season nutrient concentrations (mg l^{-1}) (NO_3^{-1} = 0.54±1.66, K^+ = 0.84±0.94, Ca^{+2} = 0.87±8.9, Na^+=0.64±0.52) were slightly higher than values estimated by Akoto et al. (2011) at a location in the southern part of Ghana (NO_3^{-1} = 0.29±3.20, K^{+1} = 0.66±0.51, Ca^{+2} = 0.89±0.95 and Na^{+1}=0.41±2.).

Wet nutrient deposition for all nutrients except Mg was highest in May; Mg values were highest in August. The trend of wet nutrient deposition for nitrate, phosphate, K and Na show that though the amount of rainfall across the region was low from February to April, the high nutrient concentrations during this period resulted in a high deposition of nutrients in these months compared to July, August, September and October when the rainfall amount was highest but was associated with a low nutrient concentration. These trends show that rather than estimating total nutrient deposition from the total annual rainfall amount (Anderson and Downing 2006), the month of rainfall collection is important in determining wet nutrient depositions across a given area.

Total wet nutrient deposition

Total annual wet nutrient deposits (95% confidence interval of mean) across the northern region of Ghana ranged from 23-120 kg km^{-2} year^{-1} nitrate-N, 3-23 kg km^{-2} year^{-1} elemental P, 185-870 kg km^{-2} year^{-1} K, 1600-4000 kg km^{-2} year^{-1} Ca, 1200 -2600 Kg km^{-2} year^{-1} Mg, and 270-1500 Kg km^{-2} year^{-1} Na (Figure 5.7).

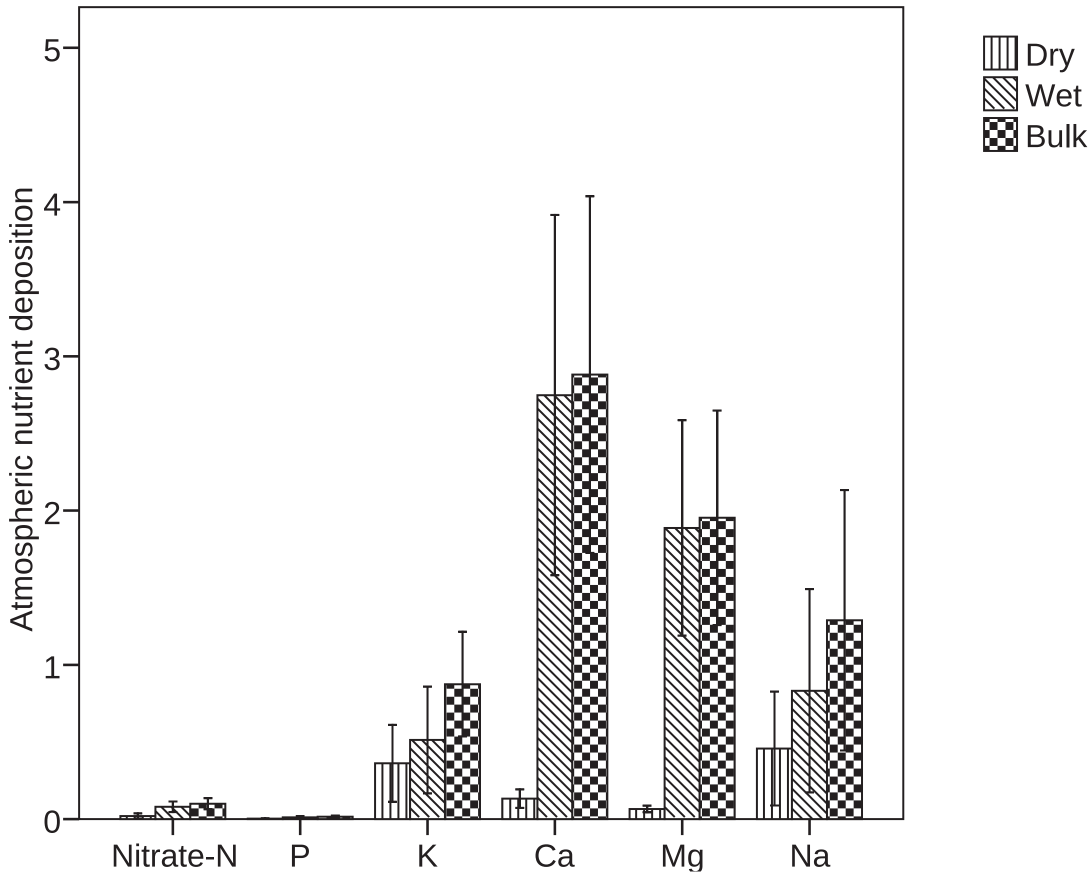

Figure 5.7 Annual atmospheric (dry, wet, bulk) nutrient depositions (Mg km^{-2}) across the northern region of Ghana from July 2010 to June 2011. Bars represent the 95% confidence interval of mean.

Wet nutrient deposits across the entire region were subsequently estimated from the total land area (70383 km^2) as 1.6-8.4 Gg of nitrate - N, 0.2-1.6 Gg elemental P, 13-61 Gg K, 115-280 Gg Ca, 84-180 Gg Mg, and 19-100 Gg Na. The quantities of nutrients annually deposited through precipitation are multiples of the quantities deposited by dry means across the northern region of Ghana. The quantity of nitrate-N deposited by rainfall is 0.5-40 times the quantity deposited by dry means. Wet P deposition was estimated to be 0.5-32 times, K = 0.3-9 times, Ca = 8-66 times, Mg = 13-64 times, and Na about 0.3-16 times the deposition by dry means.

5.3.9 Bulk nutrient deposition and net nutrient balance

The estimated bulk nutrient deposits of 26-162 Kg km^{-2} $year^{-1}$ elemental N, 3.7-29 Kg km^{-2} $year^{-1}$ elemental P, and 500-1300 Kg km^{-2} $year^{-1}$ K amounted to total atmospheric nutrient deposition of 2-11 Gg N, 0.3-2.1 Gg P, and 38-99 Gg K across the northern region of Ghana (Figure 5.7). The bulk of atmospheric nutrient deposits was 11-72% of N imported into the country, 10-80% of elemental P imports, and 500-1400% of K imports in 2007 (section 4.3.6). Annual atmospheric nutrient deposits are, therefore, an important economic source of plant nutrients for food production across Ghana and critical to the sustenance of the regional soils.

The net nutrient balance between the estimated fire-induced nutrient losses and the bulk atmospheric nutrient depositions are provided in Table 5.11. The positive nutrient balance for K, Ca, Mg and Na show that enough of these nutrients return to the system through dry and wet depositions to offset the annual gross transfers due to vegetation fires. The positive balances also show that some of these nutrients originate from sources other than regional redistribution due to vegetation fires.

Table 5.11 Net annual nutrient balance (Gg) between bush fire nutrient losses (Gg) and bulk (wet and dry) atmospheric nutrient deposition (Gg) across the northern region of Ghana. Values are 95% confidence intervals of mean.

	Gross losses		Bulk nutrient gain		Annual nutrient balance	
	Lower	Upper	Lower	Upper	Lower	Upper
N	66	215	2	11	-213	-55
P	3	18	0.3	2.1	-18	-1
K	9	37	38	91	1	82
Ca	23	76	120	290	44	267
Mg	5	26	88	190	62	185
Na	1	5.6	25	162	19.4	161

Lower = lower bound 95% confidence interval of mean, Upper = upper bound 95% confidence interval of mean

If these elements are not lost from the soil by other secondary means such as erosion and/or leaching, they should be readily available in adequate quantities for annual crop growth, and will not limit agricultural productivity across the region. The negative balance of -213 Gg to -55 Gg N, and -18 Gg to -1 Gg P indicates that these two elements are temporally being lost from soils across the region through annual burns.

Because there is currently no complete data available on the quantity of N that is actually fixed through biological N_2-fixation processes under each of the studied vegetation cover types, the estimated N balance is not complete and reflects only the balance between fire losses and bulk atmospheric nitrate-N deposition. The bulk of soil-N gains, however, come from biological N_2-fixation (Dakora and Keya 1997; Giller et al. 1994) across the individual vegetation types. Fixation of atmospheric N by most leguminous crops has been extensively studied, providing knowledge on the ability to re-supply atmospheric N to soils at the farm level. For instance, Dakora and Keya (1997) estimated the capacity of grain legumes to fix 1.5-21 Mg N km^{-2} and tree legumes to fix about 4.3-58 Mg N km^{-2}. Ahiabor et al. (2007) estimated that cowpea (*Vigna unguiculata* (L.) Walp.) fixed about 14.5 Mg N km^{-2} in test soils across the northern region of Ghana with over 90% of the fixed N coming from the atmosphere (~13 Mg km^{-2}). Given that mean N losses due to fire range from 2.8-8.1 Mg N km^{-2} (Table 4.12), most of the fire-induced N losses could be replaced through biological N_2-fixation. In situations where indigenous rhizobia do not promote substantial nodulation for atmospheric N_2-fixation, inoculations with non-native rhizobia are used to promote nodulation. Dogbe et al. (2000) reported rhizobia inoculation of mucuna to increase nodulation 3-20 fold and to increase atmospheric N_2-fixation by 18-98% using the nodulation and fixation levels of native rhizobial strains as base for comparison. Thus, besides the natural ability of indigenous leguminous species to fix atmospheric N, conventional knowledge has made it possible to increase the rate of N_2-fixation. This notwithstanding, the relative abundance of N in the atmosphere, nature's ability to fix atmospheric N through abiotic fixation processes as in oxidation during lightening (Cooray and Rahman 2005; Bian et al. 2012), and the possible industrial fixation of atmospheric N during fertilizer synthesis (e.g., during the Harber-Bosch process, Dawson and Hilton 2011) reduce the potential threat that annual bush-fire N loss poses to regional food security.

The story with P is different. It is not in abundance in nature (Elser 2012). Besides, the stock of rock phosphate used in the manufacture of P fertilizers is finite and being depleted (Dawson and Hilton 2011). The P problem across the northern region of Ghana in particular is further worsened by existing competition between plant roots and the high P sorbing iron-bearing minerals of the soils that bind P strongly under the acidic condition and make them less available to crops (Abekoe and Tiessen 1998; Owusu-Bennoah et al. 1997; Owusu-Bennoah et al. 2000). Fire has both desirable and undesirable effects on the plant available P pool of the northern region of Ghana. Sharpley (2000) reported the peak soil pH for bio-available P to be 6.5. Fire indirectly increases P availability to plants in the sesquixide-rich, slightly acidic soils by increasing the soil pH through the two processes of organic acid removal/denaturing and release of the basic cations (K, Ca, Mg, Na) in their oxide, hydroxide or carbonate forms (Arocena and Opio 2003; Certini 2005). Though high burn temperatures have been observed to reduce the concentration of gibbsite in soils (Ketterings et al. 2000; Certini 2005), they are also known to thermally transform stable goethite crystals into finer maghemite (Schwertmann and Taylor 1989; Crockford and Willett 2001) with enhanced surface area and hence potential for chemosorption of P. The enhanced sorption further reduces availability of soil P for plant uptake. Because most functions played by P in plants are not played by other elements (Elser 2012), its annual transfer to the atmosphere during bush fires and the estimated negative balance, hence potential loss from the soil, is a cause for concern. In this regard, persistent annual P deficiency due to bush fire occurrence is a threat to regional food production and the sustenance of the regional soils towards future food security.

5.3.10 Mechanism of net plant nutrient balance between bush fire losses and atmospheric depositional gains

Different parameters determine the net balance of local soil nutrients after vegetation-burn across the savanna landscape (Figure 5.8). The parameters can be grouped into localized parameters that involve all processes that occur in the soil during or after vegetation burns, and atmospheric/above-ground parameters that include all processes that occur above the soil surfaces before. All affect the temporal fate of plant nutrients.

Localized nutrient balancing mechanisms consist of complex inter-physical, chemical and biological activities that occur in the soil, that may be interrelated, and that influence each other in one way or the other.

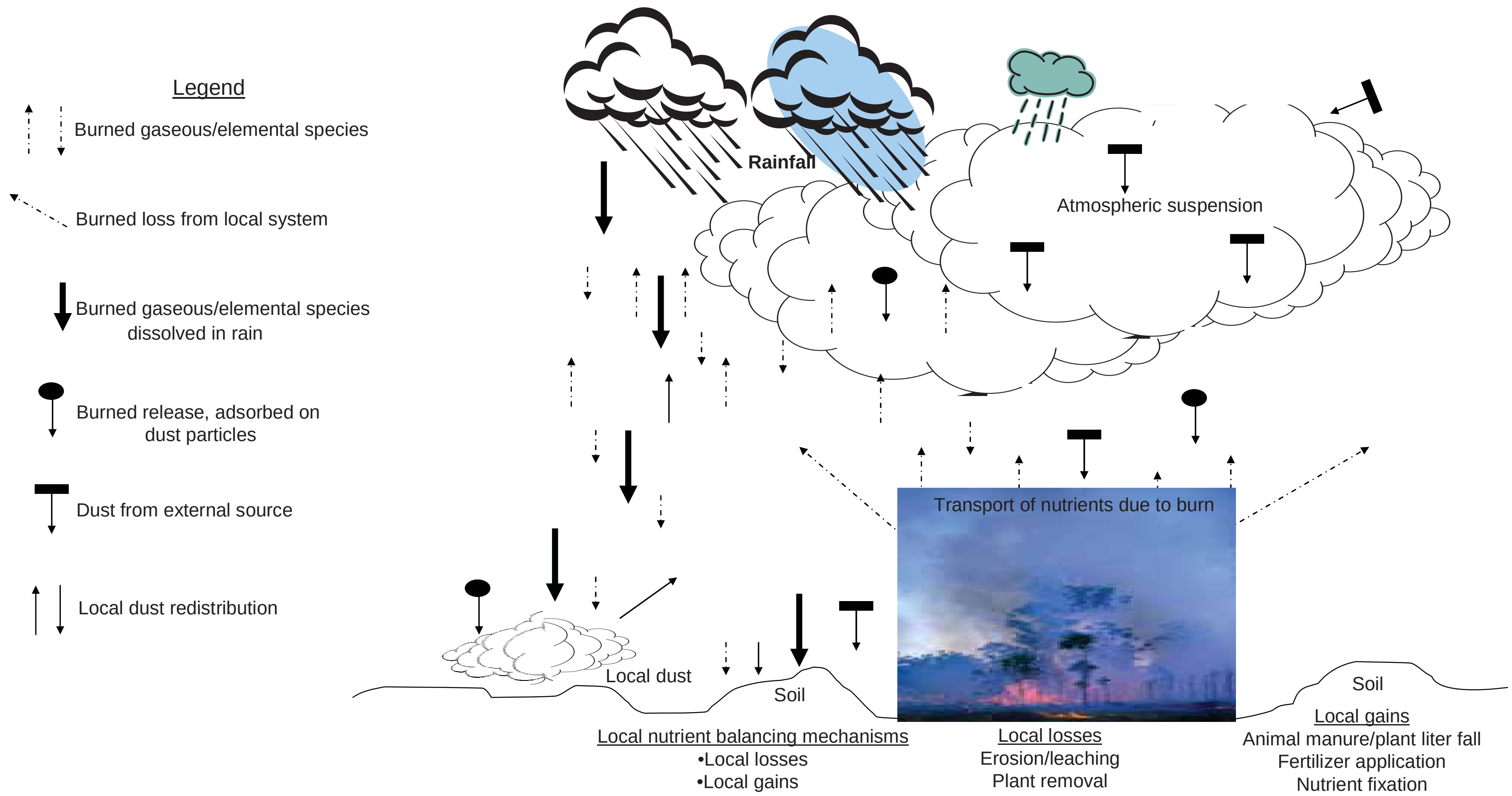

Figure 5.8 Pathways for net nutrient balance between bush fire nutrient losses and atmospheric nutrient depositions across the northern region of Ghana

High temperatures during burns kill prevailing soil macro-organisms like the earthworm, and directly reduce microbial activity and soil organic matter. These parameters in turn deteriorate soil physical properties including aeration, water infiltration and water retention, destroy the soil structure, promote compaction and reduce the soil's ability to form stable soil aggregates.

Readily available ash nutrients after burns are quickly picked up and stored in plants, resulting in vigorous vegetative growth shortly after burn per rainfall event, and less temporal nutrient availability and hence stunted growth with time. The reduced temporal growth due to nutrient drawdown is a primary factor in determining the non-establishment of forest vegetation and in determining the primary savanna vegetation structure across the region. The recycling of plant nutrients by fires is, therefore, essential for early vegetative growth, which in turn supports livestock, agriculture, wildlife, and the general ecosystem functions and human interdependence on them.

This phenomenon also indicates that should tree growth be ineffectively promoted across the savanna landscape, nutrients picked up and stored in growing trees may reduce temporal nutrient availability for crop production and hence a possible trade-off between climate change mitigation and food security. Should such an effort be made, it is critically important to supplement crop growth with fertilizer application.

The readily available ash nutrients after burn are also immobilized into microbial tissue cells. They may be eroded by wind and/or water, and leached to deeper horizons beyond plant root uptake, further impacting negatively on temporal vegetative growth of plants. Because these localized means of annual nutrient losses have been occurring for decades, this might have resulted in substantial nutrient losses, eventually resulting in a relatively stable-state savanna condition where nutrients need be annually supplied to the soil in ash form to encourage early vegetation growth for sustenance of the ecosystem's productivity. However, the relatively immobile P nature of the prevailing high sesquioxide soils, coupled with localized nutrient fixation as in microbial and abiotic fixation of atmospheric N, compensates for some local losses and so reduces the acute impacts of bush fires on the local soils. This phenomenon, however, has negative impacts on the soil in the long term. On agricultural lands, localized losses also include crop uptake from the field. However, this is compensated for by nutrient application in the form of manures and fertilizers.

Atmospheric nutrient balancing mechanisms cover a relatively extensive area and may involve regional, continental and global scale phenomena. Dust transported from external sources supplies high amounts of the cationic nutrients K, Ca, Mg and Na to the soils. Determination of the exact amounts of nutrients supplied from external sources is complicated by local dust redistribution and particulate inputs by nutrients originating from burned debris. Losses by fire mainly involve the volatilization of volatile nutrients like N, in some cases P and K (depending on the temperature and duration of burn), and the particulate transfer of non-volatile elements like Ca to the atmosphere during fires. Fire-induced, atmospherically transferred nutrients may be carried by wind currents from one geographic site to another, resulting in local loss of plant nutrients. The direction of atmospheric current at the time of nutrient transport (section 4.3.6) consequently determines the sink for these transferred nutrients. Since the north-easterly harmattan wind is the predominant atmospheric current during the dry season (Sunnu et al. 2008) when burns occur, it is likely that fire-induced nutrient transfers are transported towards the south-western part of the country along the path of the harmattan currents. In this sense, the Atlantic Ocean is a likely ultimate sink for most components of the transferred nutrients.

During the transport process, heavier debris and particulate entities may likely fall close to their local sources of origin, while relatively lighter debris and gaseous elements are transported further away. The higher the temperature of burn, therefore, the further transport of plant nutrients. Nutrients in transport are also adsorbed onto dust particles, in which case they fall relatively easily due to the enhanced gravitational effect. Dust-adsorbed nutrients, together with gaseous forms of plant nutrients, may also encounter rain, dissolve and fall to the location of rainfall.

5.3.11 Effective reduction of fire-induced P losses

Though the estimated direct fire-induced P losses are a cause for concern, annual bush fires also provide essential cultural and socio-economic goods and services (including hunting and land preparation for agriculture) at relatively low cost to most communities. Besides, the burns are favored by natural cyclic events that cannot be controlled. The accumulation of combustible vegetation materials during the wet season followed by the drying effect of the harmattan dry season enhances combustibility of the prevailing fuel load. Consequently, cyclic annual burn has evolved to closely associate with the cultural and socio-economic activities of the local people. This makes it difficult to implement strict fire-prevention means to reduce the impact of fires and the ensuing local soil-P losses. The need arises therefore, to devise means by which fires could render the beneficial goods and services they provide but at reduced P losses.

Two pathways to fire-induced P losses are identified: The direct fire-induced P losses and the indirect after-fire P losses from ash (section 4.3.4 to section 4.3.6). In order to devise an effective means of reducing the P losses, these two pathways to P losses were examined.

The quantities of ash collected during the early burn season were significantly higher than the quantities collected during the late burn season (section 4.3.2). Early-burn-season fine ash P concentration was also significantly higher than late season (t (40) = 2.1, P = 0.038).

Herbaceous plants were identified to be the most combusted fuel load material during burns (section 4.3). Phosphorus concentrations for herbaceous tissues in November (M = 0.73, SD = 0.21) were generally lower than those in January (t (40) = -2.1, P = 0.045). See Table 4.8 for the seasonal comparisons across each vegetation type and section 4.3.3 for the respective discussion. Coupled with the low late-season fuel load moisture (section 4.3.1), the high late-season plant tissue P concentration across savanna vegetation render late burns comparatively vulnerable to high P exposure to fires per unit burn fuel load than the early burns.

Furthermore, the late-burn direct P losses were generally higher than the early-burn losses (Table 4.22). Across savanna and grassland vegetation (Table 4.3), late-burn P losses were significantly higher than early-burn losses. The late-burn P loss of 402 kg km^{-2} across grassland is 3-fold the quantity (129 kg km^{-2}) lost during early burns. The observation of particular interest is the seasonal comparison across savanna vegetation (Table 4.3 and Table 4.13) on which 88% of the total burns across the northern region occur. A difference in P loss between late and early season of 90 kg km^{-2} constitute a reduction of 53% per unit burn area for early burns. Early burns across the savanna vegetation would greatly reduce gross fire-related P transfers and losses.

In essence, the significantly higher early burn ash and ash P accumulation compared to late burn accumulation means a higher susceptibility to after-fire ash P losses during early burns than during late burns. This is in contrast to the direct fire-induced P losses that are higher during the late burn season. The magnitudes of direct fire-induced P losses (%) are comparatively higher than total P remains in ash (Table 4.13). Given that the quantify of P that remains in the ash after burn may not be completely lost at the burned site while the direct fire-induced losses are actual estimated local losses, management options need to be directed towards reducing the direct losses rather than the after-fire ash P losses. This is particularly so for losses across grassland and savanna vegetation covers, where significantly higher late-burn losses were recorded (Table 4.3). Thus, the relatively higher late burn fire-induced P losses per unit burn area should be avoided, as early burns could achieve the same objective as late burns but at lower P losses, thereby ensuring a more resilient soil P security for food production.

5.4 Conclusions

Precipitation in the rainy season and dry atmospheric particulate suspensions during the harmattan season deposit plant nutrients across the northern region of Ghana. The amount of nutrient deposits varied according to the month of deposition and the geographic location of sample collection. Highest dry deposition occurred in January while highest wet nutrient deposition occurred between May and June due to the high plant nutrient concentration and rainfall amount. Rainfall nutrient concentration was lowest during the peak rainfall season due to the removal of particulate/gaseous nutrient suspensions by previous rains. Dry nutrient deposition had a positive linear relation with the eastward and the increasing latitudinal position of sample collection. While wet nutrient deposition had no apparent relation with longitudinal location of sample collection, there was an inverse relation between precipitation and the nutrients it deposits on the one hand and the latitudinal position of sample collection on the other.

Besides K deposition, which is comparable in both wet (13-61 Gg) and dry (7-43 Gg) depositions, annual amounts of nitrate-N, P, Ca, Mg and Na deposited by wet means are multiples of the amounts deposited by dry means.

There was a positive nutrient balance between direct fire-induced nutrient transfers and bulk atmospheric nutrient deposition for the plant nutrients K, Ca, Mg, and Na. The estimated negative nutrient balance for N is not complete, as depositions through biological N_2-fixation mechanisms across each vegetation type potentially balance the net N regime. The estimated negative P balance, however, suggests other means of P input into the system to sustain ecosystem productivity besides wet and dry P returns or challenges to future food production across the area are to be expected.

Efficient means of reducing the P losses without affecting the services provided by fire to the local population is essential. Use of the season of burn could be one measure. Though higher fuel loads are combusted in the early burn season than the late season, high fuel load moisture in the early season inhibits the spread of fire. This results in higher accumulation of incompletely burned ash that renders early burns comparatively vulnerable to higher after-burn P losses from ash than the late-season burns. However, the late-season burns are associated with higher quantities of direct fire-induced P losses per unit burn area due to low fuel load tissue moisture and a comparatively high amount of combusted P in plant tissues. The low moisture promotes combustibility in the late burn season and renders late burns vulnerable to total annual P losses. Early burns could provide similar services as the late season burns but are associated with lower total fire-induced P losses.

6 SUMMARY OF WORK DONE, FINDINGS, CONCLUSIONS AND RESEARCH OUTLOOK

6.1 Summary of work done

This study analyzed the spatial and temporal nutrient dynamics between fire-induced nutrient losses and bulk (wet + dry) atmospheric nutrient deposits across the northern region of Ghana. The annual fire-induced gaseous emissions and nutrient losses across the entire country were also quantified.

To do this, the area coverage of different vegetation cover types, the season of annual fire occurrence, and the seasonal burn area extent of each vegetation cover type were identified and defined for a period of 10 years (2001 to 2010) by means of remote sensing data using geo-referenced burn area data and the corresponding vegetation cover at time of burn.

The early (November) and late (January) burn-season aboveground fuel load, nutrient load (N, P, K, Ca, Mg, Na) and the C load before combustion, and in ash after combustion were determined for each combusted vegetation type after which elemental losses per unit burn area were estimated. Seasonal emissions of the gaseous products CO_2, CO, CH_4, and NO_x per unit burn area of each vegetation type were estimated from the seasonal C and N losses and the respective gaseous emission factors. The absolute values of average annual elemental losses/gaseous emissions were quantified from the estimated losses/emissions per unit burn area and the mean annual burn area of each vegetation cover. Seasonal nutrient losses/emissions by each cover type were summed to give total seasonal values after which all losses/emissions were summed to obtain the annual losses/emissions across the region.

Geospatial and temporal dry depositions and wet depositions with their constituent nutrients were quantified from July 2010 to June 2011 across the northern region of Ghana, after which the net annual nutrient balance between bush fire losses and the bulk nutrient deposits were estimated.

6.2 Main findings

6.2.1 Vegetation cover, seasonal burn occurrence and annual burn vegetations

- The main (98%) vegetation covers of Ghana are in the order savanna>cropland/natural vegetation mosaic>woody savanna>evergreen broadleaf forest >croplands >grasslands>shrubland. Across the northern region, the main (99%) vegetation covers are savanna>woody savanna>cropland/natural vegetation mosaic>grasslands> cropland >shrubland.
- ~ 100% of annual burns across the northern region take place during the dry season starting from November and ending in February the following year.
- About 57-79 thousand km^2 (25-35%) of dry land is annually burned across Ghana; 32-45 thousand km^2 of the burn occur across the northern region of the country, which constitute only 29% of the total land area. Seasonal monthly burns occur in the order December (~68%)>November (~21%)>January (~10%)>February (~1%). About 98% of the burns occur across the four land-cover types savanna (87.7%), woody savanna (9.8%), grassland (0.3%) and shrubland vegetation (0.1%). In the process, about 45-60% of the total dry land cover of the northern region of Ghana gets burned annually.

6.2.2 Fire-induced elemental losses and gaseous emissions

- Combusted fuel load varied by vegetation type, plant part and season of combustion. Mean of total combusted fuel load ranges from 326±27 to 550±45 Mg km^{-2}. Herbaceous plants are the most burned plant materials per unit burn area compared to leaves and twigs because of their relative susceptibility and high combustibility, enhanced by adequate aeration space, fuel load amount and package of fuel stock. Total combusted fuel load varies ($P < 0.001$) from one vegetation type to the other during late burns, but does not vary ($P = 0.347$) across vegetation types during early season burns. Total combusted fuel load is higher during early burns than late burns except across grassland where the opposite is observed. Ash loads are lower than fuel load before combustion and are higher in the early burn season than in late burn season.
- Concentrations of all plant nutrients (N, P, K, Ca, Mg, and Na) are higher in leaves and herbs than in twigs during both early and late burn seasons. Carbon

concentrations are, however, highest in leaves during the early burn season but highest in twigs during the late burn season. Concentration of N and C in plant parts are higher than their respective concentrations in ash after combustion, while concentrations of P, K, Ca, Mg, Na, in ash are higher than concentrations in plant tissues before combustion.

- Elemental loads before combustion are higher than elemental loads in ash after combustion for all elements. Mean ranges of elemental losses due to burn were C (134-242 thousand kg km^{-2}, 88-98% of combusted load); N (2.8-8.1 thousand kg km^{-2}, 93-97%), P (127-402, 42-77%), K (80-830, 10-68%), Ca (120-1040, 11-76%), Mg (60-390, 24-68%), and Na (32-154, 36-90%). Season of burn has varying influences on elemental losses per unit burn area. For instance, P losses are higher during late burns than in early burns while N losses are highest during early burns than in late burns. Carbon losses showed no significant seasonal variations.
- Across the northern region of Ghana, the absolute gross fire-induced plant nutrient losses (Gg $year^{-1}$) amount to 66-216 N, 3-18 P, 9-37 K, 23-76 Ca, 1-5.6 Na. Across entire Ghana, the losses amount to 116-400 N, 6-33 P, 16-70 K, 34-128 Ca, 7.8-45 Mg, and 2-10 Na, respectively.
- Absolute annual fire-induced gaseous emissions (Gg $year^{-1}$) across the northern region of Ghana amount to 21-57 thousand CO_2, 0.3-2.8 thousand CO, 4-118 CH_4, and 29-175 $NO_{x.}$ Across entire Ghana, the emissions amount to about 33-99 thousand CO_2, 0.5-5 thousand CO, 8-200 CH_4, and 45-300 NO_x.

6.2.3 Geospatial and temporal dry atmospheric nutrient depositions

- Month and latitudinal position are the greatest predictors of quantity of dry deposits and dry nutrient deposits across the northern region of Ghana. Dry nutrient depositions linearly correlate with latitude.
- Estimated mean of monthly nutrient concentrations (mg kg^{-1}) of dry harmattan season deposits are 110-2800 nitrate (24-640 nitrate-N), 70-170 phosphate (23-55 elemental P), 2700-4150 K, 1600-2000 Ca, and 740-930 Mg, and are higher than nutrient extracts from soils of same sampling locations. The Na concentrations of the dry deposits are higher than expected.

- Estimated (95% confidence interval of mean) annual harmattan season dry deposits (kg km^{-2}) across the northern region of Ghana during the 2010-2011 dry season amount to 53-122 thousand, 3-42 nitrate-N, 0.7-6.3 P, 100-618 K, 70-200 Ca, 40-90 Mg, and 90-820 Na.

6.2.4 Geospatial and temporal wet atmospheric nutrient depositions

- Month of deposition determines the nutrient concentration of rainfall and the quantity of deposition. For a given month, latitude is the greatest geospatial predictor of wet nutrient depositions. Latitude does not have any apparent relation with the concentrations of plant nutrients but inversely correlates with the quantities of wet nutrient deposits.
- Mean monthly rainfall nutrient concentrations are highest during the early rainfall season and lowest during the peak rain season.
- Total annual wet nutrient deposits (95% confidence interval of mean) across the northern region of Ghana (Kg km^{-2} $year^{-1}$) amount to 23-120 nitrate-N, 3-23 elemental P, 185-870 K, 1600-4000 Ca, 1200-2600 Mg, and 270-1500 Na.

6.2.5 Nutrient balance between annual fire losses and bulk atmospheric deposition

- The net nutrient balance (Gg) between fire-induced elemental transfers and bulk (dry + wet) atmospheric nutrient depositions across the northern region of Ghana are negative for N and P; and positive for K, Ca, Mg, and Na. The negative N balance only reflects losses by fires and bulk atmospheric inputs of nitrate-N. Nitrogen gains through nitrogen fixations across each vegetation type were not captured in this study.

6.3 Conclusions

Reduced tree growth due to the impact of annual fires contributes to the establishment of savanna vegetation as the predominant vegetation type across the northern region of Ghana. Adequate timing of rain and onset of the dry season enhance cyclical accumulation of fuel load that becomes vulnerable to burn in the dry season. This annual phenomenon leads to consistent dry-season burns that have evolved to closely associate with the cultural and socio-economic activities of the local people, offering them economic livelihoods by providing goods and services such as the use of fire in land preparation for agriculture at a relatively low cost. The socio-economic benefits of annual fires render proposed fire-prevention mechanisms difficult to implement. Such mechanisms should not, therefore, aim at fire prevention but at means by which annual fires could maintain the cyclic goods and services they provide but at a reduced impact on general environmental productivity.

Gross losses of P, K, Ca, Mg, and Na in particulate and non-particulate forms during burns and from ash after burns result in local losses of these nutrients from the burned sites: A fire-induced elemental drawdown effect that could impact local food production. Elemental losses during fires are multiples of the quantity annually imported into the country in the form of fertilizers, making fire-induced nutrient losses significant economic losses to the nation. Because early burns are associated with comparatively high fuel load moisture content, better plant growth condition and hence elemental concentrations, they are associated with high elemental losses per unit burned dry matter. However, the high moisture content impedes the burn, resulting in patches of burned and unburned land that could promote wildlife sustenance and reduce late-season burns. Besides, the high late-burn fuel load amount and low late-season fuel load moisture content enhance late burns and make them susceptible to higher total nutrient losses.

Highest N-related emissions occur in the early burn season due to high absolute N content of combusted fuel, while comparable C-related emissions occur in both seasons. However, early burns are impeded by high tissue moisture content and reduced combustibility, which renders late burns comparatively vulnerable to total annual emissions. Early burns enhance tree seedling establishment and subsequent carbon capture and storage while maintaining ecological productivity through the patches they create. Though a low combustion of carbon in twigs implies a safe storage and conservation of carbon in woody parts of plants, the fires, through heat stress, hinder the establishment of young tree seedlings across the savanna and woody savanna vegetation. This in turn reduces the temporal C sequestration potentials of the prevailing savanna system.

The sources of dry nutrient deposits vary, with burned debris contributing to high dry deposition nutrient concentrations. Highest wet nutrient deposition occurs between May and June due to high nutrient concentration and rainfall amount. Low rainfall nutrient concentration during the peak rainy season is attributed to an atmospheric cleansing effect by previous rains. Besides K deposition (kg km^{-2}) across the northern region, which is comparable in both wet and dry depositions, annual amounts of nitrate-N, P, Ca, Mg and Na deposited by wet means are multiples of the amounts deposited by dry means.

The net negative balance for P is a call for concern given that the soils are inherently low in plant available P, and the nutrient is bound by the high sesquioxide minerals of the soils and rendered relatively unavailable for uptake by plant roots. The negative P balance also suggests the existence of other means of P input into the system to sustain the ecosystem's productivity besides wet and dry P returns, or predict challenges to future food production across the area.

In order to reduce the gross fire-induced P-losses, early- dry season -burns are recommended as these are associated with significantly low P losses when compared with late burns.

6.4 Future research outlook and research recommendations

Based on the findings and limitations of this study, further research is recommended on the following:

- There is the need to look at burn areas on a finer resolution scale when data become increasingly available. Use of the current 500 m resolution pixel images are too coarse to capture relatively small burned areas, especially burns across smaller farms, which are the predominant farm sizes across the study area and from where elemental losses and emissions might be high due to fertilizer applications.
- Emission factors vary from one region to another and by season. There is a need to estimate country-based seasonal emission factors for the various vegetation types as these are currently not available, rendering current estimations dependent on annual global emission factors estimated across similar vegetation types.

- Research on biological N_2-fixation across each natural vegetation type in Ghana is essential in estimating an overall nutrient balance.
- In order to implement effective fire management strategies, it is necessary to create a database on fire-induced emission and nutrient loss at the decision-making district and municipality level to aid in monitoring and evaluating annual progress in fire controlling programs.
- Geospatial distribution of wet and dry nutrient deposits across the southern section of the country need be investigated in order to know their southwards distribution and to afford a ground-data-based means of estimating the balance across the entire country.
- There is the need also to replicate, a number of times, the entire work done in this study, particularly the distribution of wet and dry deposits, in order to estimate and appreciate the inter-annual variabilities in these parameters.

7 REFERENCES

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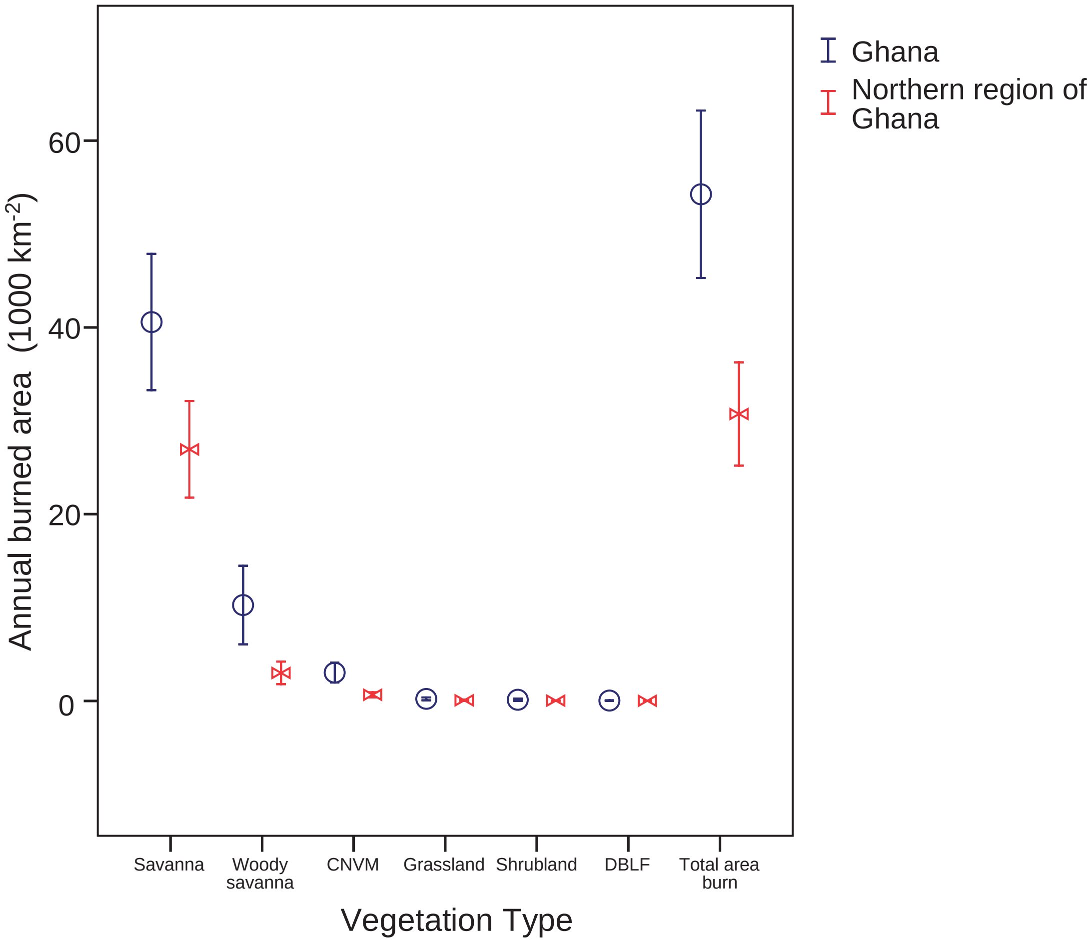
8 APPENDICES

Appendix 1 Total land area of different vegetation cover types burned annually across Ghana and the northern region of Ghana from 2001-2010. Bars represent 95% confidence interval of mean. Monthly inter-vegetation type area burns are provided in Figure 3.2



Appendix 2 Variations in plant tissue moisture content, plant tissue fuel load and combusted plant tissue elemental load across the northern region of Ghana in November 2010 and January 2011. Values are means, standard deviation in brackets below the mean value

		Leaves	Herbs	Twigs	Sig level
		Moisture (%)			
November		35	32	29	0.196
		(23)	(12)	(22)	
January		15^{b}	15^{b}	25^{a}	0.001
		(17)	(8)	(21)	
		Fuel load (kg km^{-2})			
November	Load	49600^{b}	353000^{a}	34000^{b}	<0.001
		(69000)	(203000)	(39000)	
	C	22000^{b}	153000^{a}	14000^{b}	<0.001
		(31000)	(88700)	(17000)	
	N	1000^{b}	5000^{a}	550^{b}	<0.001
		(1300)	(3430)	(608)	
	P	33^{b}	255^{a}	25^{b}	<0.001
		(44)	(164)	(34)	
	K	109^{b}	860^{a}	50^{b}	<0.001
		(150)	(510)	(80)	
	Ca	160^{b}	1060^{a}	90^{b}	<0.001
		(220)	(630)	(100)	
	Mg	60^{b}	310^{a}	44^{b}	<0.001
		(86)	(190)	(50)	
	Na	14^{b}	130^{a}	8^{b}	<0.001
		(19)	(90)	(14)	
January	Load	83800^{b}	302000^{a}	27700^{b}	<0.001
		(119000)	(203000)	(41400)	
	C	38000^{b}	134000^{a}	11800^{b}	<0.001
		(54000)	(94300)	(18200)	
	N	1060^{b}	2400^{a}	300^{c}	<0.001
		(1500)	(1700)	(450)	
	P	61^{b}	260^{a}	17^{b}	<0.001
		(99)	(190)	(20)	
	K	260^{b}	780^{a}	60^{c}	<0.001
		(420)	(300)	(100)	
	Ca	220^{b}	840^{a}	80^{b}	<0.001
		(330)	(570)	(100)	
	Mg	80^{b}	330^{a}	26^{b}	<0.001
		(120)	(240)	(38)	
	Na	18^{b}	90^{a}	5^{b}	<0.001
		(27)	(70)	(5)	

Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different plant tissues

Appendix 3 Variations in plant tissue elemental concentrations (mg g^{-1}) across the northern region of Ghana in November 2010 and January 2011. Values are means, standard deviation in brackets below the mean value

		Leaves	Herbs	Twigs	Sig level
November	C	432^{a}	433^{a}	406^{b}	0.010
		(38)	(17)	(60)	
	N	20.6^{a}	14.7^{b}	16^{b}	<0.001
		(3.9)	(4.6)	(3.7)	
	C:N	22^{c}	33^{a}	27^{b}	<0.001
		(4)	(12)	(8)	
	P	0.7	0.74	0.73	0.708
		(0.16)	(0.2)	(0.25)	
	N:P	31^{a}	21^{c}	25^{b}	<0.001
		(8)	(5)	(11)	
	K	2.2^{a}	2.5^{a}	1.5^{b}	<0.001
		(0.52)	(0.45)	(0.81)	
	Ca	3.2^{a}	3.0^{a}	2.6^{b}	<0.001
		(0.61)	(0.42)	(0.65)	
	Mg	1.2	1	1.2	0.125
		(0.43)	(0.47)	(0.68)	
	Na	0.3^{a}	0.4^{a}	0.25^{b}	0.001
		(0.11)	(0.13)	(0.16)	
January	C	453^{ab}	444^{b}	455^{a}	0.036
		(13)	(17)	(22)	
	N	12.8^{a}	8.5^{b}	11.5^{a}	<0.001
		(2.1)	(2.1)	(3.6)	
	C:N	36^{c}	57^{a}	44^{b}	<0.001
		(5)	(17)	(13)	
	P	0.7^{b}	0.83^{a}	0.64^{b}	0.005
		(0.21)	(0.19)	(0.25)	
	N:P	20^{a}	12^{b}	20^{a}	<0.001
		(7)	(5)	(10)	
	K	2.5^{ab}	2.9^{a}	2.2^{b}	0.005
		(0.71)	(0.81)	(0.91)	
	Ca	2.7^{ab}	2.9^{a}	2.5^{b}	0.005
		(0.58)	(0.51)	(0.31)	
	Mg	1^{b}	1.1^{a}	1^{b}	0.017
		(0.31)	(0.26)	(0.27)	
	Na	0.2^{b}	0.3^{a}	0.2^{b}	<0.001
		(0.07)	(0.11)	(0.11)	

Values with different superscripted letters (horizontal direction) show significant differences ($P \leq 0.05$) across the different plant tissues

Appendix 4 Gross annual and inter-seasonal carbon/nitrogen losses (Gg) by different vegetation cover types due to bush fire occurrence across the northern region of Ghana and across Ghana. Values are 95% confidence interval of mean estimated from field quantified gross elemental loss per unit area across the study area and the seasonal area of each vegetation type burned over a 10 year period (2001-2010)

	November		December		January		February		Annual Total	
	Low	Upp	Low	Upp	Low	Upp	Low	Upp	Low	Upp
Carbon										
Northern region of Ghana										
Savannas	720	2700	3900	8300	260	1000	20	110	4930	12100
WS[1]	10	110	450	1300	0	170	1	20	460	1570
CNVM[2]	5	40	30	110	6	30	1	5	40	180
Grassland	0	10	0	30	0	10	0	3	0	60
Shrubland	0	3	1	10	0	3	0	0	1	15
Ghana										
Savannas	1630	5200	5320	11600	330	1200	20	110	7300	18100
WS[1]	10	160	1070	3000	100	1500	10	130	1190	4800
CNVM[2]	20	80	90	320	50	400	30	90	180	890
Grassland	0	40	10	60	4	40	0	10	10	150
Shrubland	1	8	1	20	0	40	0	5	2	70
Nitrogen										
Northern region of Ghana										
Savannas	21	97	36	76	4	18	0.2	1.2	61	192
WS[1]	0.4	5.6	4.3	11	0	3.9	0.01	0.1	5	21
CNVM[2]	0.1	0.8	0.3	0.9	0.09	0.5	0.01	0.03	0.5	2
Grassland	0	0.2	0	0.2	0	0.2	0	0.02	0	1
Shrubland	0	0.1	0.01	0.1	0	0.1	0	0	0	0.3
Ghana										
Savannas	48	187	48	105	5.1	22	0.2	1.3	101	315
WS[1]	0.5	8	10	26	1.7	35	0.1	1	12	70
CNVM[2]	0.4	1.5	0.8	2.6	0.7	7.6	0.2	0.6	2	12
Grassland	0	0.8	0.1	0.5	0.06	0.8	0	0.08	0.2	2
Shrubland	0.03	0.4	0.01	0.2	0	1	0	0.06	0	2

Low = lower bound, Upp = Upper bound, WS[1]: Woody savanna, CNVM[2]: Cropland/Natural Vegetation Mosaic, distribution = Delta distribution with a modified Bessel function of the second order

Appendix 5 Gross annual and inter-seasonal P and K losses (Gg) by different vegetation cover types due to bush fire occurrence across the northern region of Ghana and across Ghana. Values are 95% confidence interval of mean estimated from field quantified gross elemental loss per unit area across the study area and the seasonal area of each vegetation type burned over a 10 year period (2001-2010)

	November		December		January		February		Annual Total	
	Low	Upp	Low	Upp	Low	Upp	Low	Upp	Low	Upp
Phosphorus										
Northern region of Ghana										
Savannas	490	2500	760	9800	350	1400	6	54	1602	13000
WS[1]	10	210	1330	3900	0	240	2	36	1350	4400
CNVM[2]	3	30	2	180	9	40	1	5	15	260
Grassland	0	8	0	50	0	20	0	3	0	80
Shrubland	0	3	0	10	0	4	0	0	0	20
Ghana										
Savannas	1100	4800	1000	12500	430	1700	10	60	2600	19000
WS[1]	10	310	3100	9100	80	2200	20	300	3300	11900
CNVM[2]	10	50	6	540	80	700	20	100	111	1400
Grassland	0	30	1	100	6	70	0	10	7	210
Shrubland	0	10	0	30	0	46	0	2	0	90
Potassium										
Northern region of Ghana										
Savannas	1200	9500	4900	16000	390	2600	10	190	6500	28600
WS[1]	10	400	2400	6600	0	600	2	60	2400	7650
CNVM[2]	10	160	80	340	20	100	1	10	100	610
Grassland	0	50	1	90	0	50	0	10	1	200
Shrubland	0	5	1	20	0	20	0	1	1	40
Ghana										
Savannas	2800	18300	6600	22600	480	3200	10	200	9900	44000
WS[1]	10	600	5600	15500	140	5600	30	460	5800	22000
CNVM[2]	50	300	200	1000	140	1600	40	200	400	3100
Grassland	0	170	20	180	10	160	0	30	30	500
Shrubland	0	10	2	50	0	200	0	10	2	280

Low = lower bound, Upp = Upper bound, WS[1]: Woody savanna, CNVM[2]: Cropland/Natural Vegetation Mosaic, distribution = Delta distribution with a modified Bessel function of the second order

Appendix 6 Gross annual and inter-seasonal Ca, Mg and Na losses (Mg) by different vegetation cover types due to bush fire occurrence across the northern region of Ghana and across Ghana. Values are 95% confidence interval of mean estimated from field quantified gross elemental loss per unit area across the study area and the seasonal area of each vegetation type burned over a 10 year period (2001-2010)

	November		December		January		February		Annual Total	
	Low	Upp	Low	Upp	Low	Upp	Low	Upp	Low	Upp
Calcium										
Northern region of Ghana										
Savannas	690	10800	19600	52882	867	3521	12	200	21200	67400
WS[1]	20	400	1470	6168	0	832	5	80	1500	7500
CNVM[2]	20	200	130	598	20	120	4	30	170	1000
Grassland	0	60	1	162	0	63	0	20	1	300
Shrubland	0	10	2	50	0	9	0	1	2	70
Ghana										
Savannas	1553	20900	26600	73500	1100	4200	10	210	29000	99000
WS[1]	23	600	3500	14600	230	7400	50	600	3800	23000
CNVM[2]	84	410	340	1800	170	2000	120	500	700	4600
Grassland	0	220	30	310	10	200	0	60	40	800
Shrubland	0	20	4	120	0	100	0	10	4	250
Magnesium										
Northern region of Ghana										
Savannas	150	3050	4200	16200	260	1800	60	500	4600	21600
WS[1]	10	160	480	3800	0	360	3	50	500	4400
CNVM[2]	1	10	3	30	10	50	0	6	10	100
Grassland	0	4	0	10	0	20	0	4	0	40
Shrubland	0	3	1	30	0	3	0	2	1	40
Ghana										
Savannas	340	5900	5600	22600	320	2200	70	510	6400	31200
WS[1]	10	240	1100	9000	100	3200	40	410	1300	13000
CNVM[2]	4	30	10	80	60	780	120	120	80	100
Grassland	0	10	1	20	5	80	0	15	6	120
Shrubland	0	10	2	7	0	40	0	30	2	150
Sodium										
Northern region of Ghana										
Savannas	450	2150	270	2150	80	550	1	10	800	4860
WS[1]	4	70	140	490	0	70	0	2	140	640
CNVM[2]	3	30	20	50	2	15	0	1	25	100
Grassland	0	10	0	10	0	10	0	1	0	30
Shrubland	0	1	0	2	0	1	0	0	0	4
Ghana										
Savannas	1020	4160	370	3000	100	660	1	12	1490	7830
WS[1]	5	110	330	1160	20	610	1	14	360	1890
CNVM[2]	10	60	50	150	20	250	5	20	80	480
Grassland	0	40	3	30	1	30	0	3	4	90
Shrubland	0	4	0	4	0	10	0	1	0	20

Low = lower bound, Upp = Upper bound, WS[1]: Woody savanna, CNVM[2]: Cropland/Natural Vegetation Mosaic, distribution = Delta distribution with a modified Bessel function of the second order

Appendix 7 Gross annual and inter-seasonal greenhouse gas emission (CO_2, CH_4) by different vegetation cover types due to bush fire occurrence across the northern region of Ghana and across Ghana. Values are 95% confidence interval of mean estimated from field quantified combusted fuel load, the mean seasonal area of each vegetation-burned over a 10 year period (2001-2010), and the respective emission factors (g gaseous emission kg^{-1} combusted fuel load) per vegetation type

	November		December		January		February		Annual Total	
	Low	Upp	Low	Upp	Low	Upp	Low	Upp	Low	Upp
CO_2 (Gg)										
Northern region of Ghana										
Savannas	2823	11601	14763	33238	1072	4238	65	438	18723	49516
WS[1]	34	499	1733	5343	0	728	5	68	1772	6639
CNVM[2]	19	167	155	434	21	98	4	18	200	717
Grassland	0	48	2	117	0	52	0	11	2	229
Shrubland	0	13	3	35	0	13	0	1	3	63
Ghana										
Savannas	6378	22442	20021	46226	1317	5115	73	457	27789	74241
WS[1]	49	727	4091	12608	385	6501	52	554	4576	20391
CNVM[2]	69	314	416	1279	181	1626	102	349	768	3567
Grassland	0	170	32	225	14	167	0	45	46	607
Shrubland	3	37	5	82	0	152	0	22	9	292
CH_4 (Gg)										
Northern region of Ghana										
Savannas	0.5	24	2.5	68	0.2	9	0	0.9	3.2	101
WS[1]	0	1.1	1.2	12	0	1.6	0	0.2	1.2	15
CNVM[2]	0	0.3	0	0.9	0	0.2	0	0	0	1.5
Grassland	0	0.1	0	0.2	0	0.1	0	0	0	0.5
Shrubland	0	0	0	0.1	0	0	0	0	0	0.1
Ghana										
Savannas	1.1	46	3.4	95	0.2	10	0	0.9	5	152
WS[1]	0	1.6	3	28	0.3	14	0	1.2	3.1	45
CNVM[2]	0	0.6	0.1	3	0	3.3	0	0.7	0.1	7
Grassland	0	0.3	0	0.5	0	0.3	0	0.1	0	1.2
Shrubland	0	0.1	0	0.2	0	0.3	0	0	0	0.6

Low = lower bound, Upp = Upper bound, WS[1]: Woody savanna, CNVM[2]: Cropland/Natural Vegetation Mosaic, distribution = MeijerG function

Appendix 8 Gross annual and inter-seasonal pollutant emissions (CO, NO_x) by different vegetation cover types due to bush fire occurrence across the northern region of Ghana and across Ghana. Values are 95% confidence interval of mean estimated from field quantified combusted fuel load, the mean seasonal area of each vegetation-burned over a 10 year period (2001-2010), and the respective emission factors (g gaseous emission kg^{-1} combusted fuel load) per vegetation type

	November		December		January		February		Annual Total	
	Low	Upp	Low	Upp	Low	Upp	Low	Upp	Low	Upp
CO (Gg)										
Northern region of Ghana										
Savannas	34	569	180	1630	13	208	0.8	21	229	2428
WS[1]	1	26	44	277	0	38	0.1	3.5	45	344
CNVM[2]	0.2	8	1.9	21	0.3	4.8	0	0.9	2.4	35
Grassland	0	2.4	0	6	0	2.5	0	0.6	0	11
Shrubland	0	0.7	0.1	1.8	0	0.7	0	0.1	0.1	3.3
Ghana										
Savannas	78	1100	245	2267	16	251	0.9	22	339	3640
WS[1]	1.2	38	104	654	10	337	1.3	29	116	1058
CNVM[2]	0.8	15	5	63	2.2	80	1.2	17	9	175
Grassland	0	8	0.4	11	0.2	8	0	2.2	0.6	30
Shrubland	0.1	2	0.1	4.3	0	8	0	1.1	0.2	15
NO_x (Gg)										
Northern region of Ghana										
Savannas	4	36	21	103	1.6	13	0.1	1.4	27	154
WS[1]	0	1.4	1.5	15	0	2.1	0	0.2	1.5	19
CNVM[2]	0	0.5	0.2	1.3	0	0.3	0	0.1	0.3	2.2
Grassland	0	0.2	0	0.4	0	0.2	0	0	0	0.7
Shrubland	0	0	0	0.1	0	0	0	0	0	0.2
Ghana										
Savannas	9	70	29	144	2	16	0	1	40	231
WS[1]	0	2	3	36	0	19	0	2	4	59
CNVM[2]	0	1	1	4	0	5	0	1	1	11
Grassland	0	1	0	1	0	1	0	0	0	2
Shrubland	0	0.1	0	0.2	0	0.4	0	0.1	0	1

Low = lower bound, Upp = Upper bound, WS[1]: Woody savanna, CNVM[2]: Cropland/Natural Vegetation Mosaic, distribution = MeijerG function

Appendix 9 Chemical properties of soils sampled at the locations for sampling the wet and dry atmospheric deposits. The table also shows reported concentrations of plant nutrients in dry depositions for comparison with estimated values of this study.

	N (%)	OC (%)	O M (%)	P	K	Ca	Mg	Na
Sampling sites								
Wa	0.08	1	1.73	14	15	460	110	6
Nasia	0.05	0.92	1.59	17	34	540	120	4
Katani	0.05	1	1.82	14	29	440	210	7
Jindabuo	0.05	0.94	1.7	12	21	550	110	7
Pong Tamale	0.11	0.69	1.25	13	39	640	160	6
Pion	0.05	1.04	1.8	16	22	520	110	4
Sawla	0.05	1	1.75	21	37	500	220	5
Jeregu	0.08	0.84	1.47	18	21	650	120	4
Adibo	0.07	0.42	0.74	11	27	580	110	6
Sakpa	0.07	0.57	1	13	29	440	180	10
Wangasi Turu	0.09	0.71	1.22	15	26	640	160	7
Bimbila	0.06	0.64	1.1	12	13	540	220	3
Banda Nkwanta	0.09	0.6	1.03	22	38	490	160	9
Meriche	0.1	0.68	1.18	11	34	620	250	11
Katajelli	0.06	0.85	1.47	21	48	450	220	5
Mean	0.07	0.79	1.39	15	29	537	164	6.3
Std Error	0.01	0.05	0.09	0.95	2.5	19	13	0.6
Soils of Harmattan-dust sources								
	[1] 0.043	---	---	[7] 2.3-6.9	---	---	---	---
		---	---	[6] 3.2-14.6	---	---	---	---
Dust nutrient concentrations								
	[1] 0.057	---	---	[1] 150	[1] 1940	---	---	---
		---	---	[4] 930	[4]10120	[4] 2428	[4] 4763	[4] 16100
		---	---	[5] 1710	[5] 13770	[5] 126070	[5] 15560	[5] 5420
	[2] 0.24-0.74	---	---	[2]2557-2360	[2]11000-22000	[2]6000-25000	[2]4000-9000	[2]3500-4600
		---	---	[3]655-2007	[3]12000-46000	[3]10000-102000	[3]5000-23000	[3]4000-25000

N = Tatal N, OC = Organic carbon, OM = Organic matter, P = Available P (Bray no 1, mg kg^{-1}), K, Ca, Mg and Na are exchangeable fractions (mg kg^{-1}), [1] = Mean values of Sadoré, Niger (Sterk et al. 1996), [2] =sampling site is north to south transect of eastern West Africa Hermann et al. (2010), values are estimated mean value ranges; [3] =global compilation (Lawrence and Neff 2009), values are minimum and maximum estimates,[4 – 5] = Washington et al. (2009) ([4] = Bodélé,[5] = western sahara), 6 = Sadore Niger (Michels and Bielders 2006), 7 = Niger (Bationo and Ntare 2000).

Appendix 10 Other physico-chemical properties of soils at locations for sampling the wet and dry atmospheric deposits

	CEC	pH (Ca Cl_2)	Sand (%)	Silt (%)	Clay (%)	BD
Wa	6.27	5.52	65.50	28.20	6.30	1.56
Nasia	3.96	5.53	47.80	43.40	8.80	1.32
Katani	5.14	5.70	55.20	37.70	7.10	1.49
Jindabuo	4.09	5.50	47.40	45.70	6.90	1.30
Pong Tamale	5.72	5.65	55.60	39.40	5.00	1.36
Pion	4.08	5.67	52.90	42.20	4.90	1.39
Sawla	4.69	5.66	56.70	34.10	9.20	1.34
Jeregu	4.17	5.61	52.50	38.30	9.20	1.48
Adibo	6.22	5.79	50.30	42.30	7.40	1.56
Sakpa	6.91	5.72	65.80	27.50	6.70	1.39
Wangasi Turu	5.81	5.80	55.40	37.70	6.90	1.34
Bimbila	4.42	5.65	64.70	28.60	6.70	1.39
Banda Nkwanta	5.68	5.63	56.90	35.50	7.60	1.33
Meriche	6.22	5.79	53.60	38.50	7.90	1.27
Katajelli	4.41	5.59	47.70	45.10	7.20	1.54
Mean	5.19	5.65	55.20	37.61	7.19	1.40
Std Error	0.25	0.02	1.58	1.53	0.33	0.03

CEC: Cation exchange capacity (cmol $^{+}$ Kg $^{-1}$), BD: Bulk density (g cm^{-3})

Appendix 11 Pearson's correlation matrix for the spatial distribution of monthly dry deposited nutrient concentrations (mg kg^{-1}) and monthly inter-nutrient concentration correlations across the northern region of Ghana during the 2010-2011 Harmattan dry season. Values are coefficients, significant level (two-tail) in brackets. Significant (P < 0.05) correlations are defined by linear regressions presented in Table 5.4

	Ca	Mg	K	Na	Nitrate	Phosphate	Longitude	Latitude
				November				
Dust amount	-0.24	-0.19	-0.05	-0.14	-0.25	0.54	0.02	**0.72
	(0.43)	(0.51)	(0.88)	(0.73)	(0.41)	(0.09)	(0.95)	(0.00)
Ca	1	**0.86	0.16	*0.71	0.08	-0.42	-0.11	-0.10
		(0.00)	(0.64)	(0.03)	(0.80)	(0.22)	(0.72)	(0.74)
Mg		1	-0.43	0.61	0.07	*-0.62	0.05	-0.12
			(0.16)	(0.08)	(0.82)	(0.04)	(0.88)	(0.69)
K			1	0.19	0.02	0.32	0.13	-0.15
				(0.65)	(0.94)	(0.40)	(0.69)	(0.63)
Na				1	0.11	-0.27	0.19	0.53
					(0.79)	(0.60)	(0.62)	(0.15)
Nitrate					1	-0.18	0.15	-0.49
						(0.62)	(0.63)	(0.09)
Phosphate						1	-0.02	0.55
							(0.95)	(0.08)
				December				
Dust amount	-0.06	0.12	0.34	0.47	0.09	-0.21	0.17	**0.88
	(0.84)	(0.67)	(0.24)	(0.20)	(0.79)	(0.48)	(0.54)	(0.00)
Ca	1	*0.55	-0.37	*-0.70	-0.15	0.52	-0.02	0.08
		(0.04)	(0.20)	(0.04)	(0.64)	(0.07)	(0.94)	(0.79)
Mg		1	0.13	-0.25	-0.06	0.29	-0.40	0.32
			(0.67)	(0.52)	(0.86)	(0.34)	(0.14)	(0.25)
K			1	**0.83	-0.08	0.52	-0.24	0.47
				(0.01)	(0.81)	(0.08)	(0.41)	(0.09)
Na				1	0.72	0.69	0.33	0.26
					(0.07)	(0.06)	(0.38)	(0.49)
Nitrate					1	*0.63	0.30	0.19
						(0.05)	(0.34)	(0.55)
Phosphate						1	0.00	0.11
							1.00	(0.72)

Appendix 12 Pearson's correlation matrix for the spatial distribution of monthly dry deposited nutrient concentrations (mg kg^{-1}) and monthly inter-nutrient concentration correlations across the northern region of Ghana during the 2010-2011 Harmattan dry season. Values are coefficients, significant level (two-tail) in brackets. Significant (P < 0.05) correlations are defined by linear regressions presented in Table 5.4

	Ca	Mg	K	Na	Nitrate	Phosphate	Longitude	Latitude
				January				
Dust amount	-0.30	-0.35	-0.19	-0.52	-0.23	0.14	0.19	**0.81
	(0.27)	(0.21)	(0.50)	(0.09)	(0.50)	(0.64)	(0.50)	(0.00)
Ca	1	**0.89	-0.06	-0.34	0.56	-0.03	-0.28	-0.25
		(0.00)	(0.84)	(0.28)	(0.07)	(0.93)	(0.31)	(0.36)
Mg		1	0.07	-0.24	0.49	-0.09	-0.28	-0.23
			(0.80)	(0.46)	(0.12)	(0.76)	(0.32)	(0.41)
K			1	0.24	-0.25	0.09	0.41	-0.01
				(0.46)	(0.45)	(0.76)	(0.13)	(0.97)
Na				1	0.18	-0.16	0.01	-0.48
					(0.65)	(0.61)	(0.98)	(0.11)
Nitrate					1	0.13	-0.28	-0.25
						(0.71)	(0.41)	(0.46)
Phosphate						1	-0.34	0.46
							(0.23)	(0.10)
				February				
Dust amount	*-0.58	**-0.69	-0.04	**0.81	0.43	-0.45	0.49	*0.60
	(0.02)	(0.00)	(0.90)	(0.00)	(0.15)	(0.10)	(0.06)	(0.02)
Ca	1	**0.79	0.00	*-0.68	0.03	0.24	*-0.53	-0.35
		(0.00)	(0.99)	(0.02)	(0.91)	(0.42)	(0.04)	(0.21)
Mg		1	0.17	**-0.79	-0.37	0.43	-0.29	-0.43
			(0.53)	(0.00)	(0.22)	(0.13)	(0.29)	(0.11)
K			1	-0.07	-0.35	-0.32	-0.02	0.31
				(0.83)	(0.24)	(0.26)	(0.94)	(0.26)
Na				1	0.50	-0.23	0.34	0.42
					(0.14)	(0.53)	(0.31)	(0.19)
Nitrate					1	0.00	-0.28	0.23
						(0.99)	(0.36)	(0.45)
Phosphate						1	-0.17	-0.32
							(0.57)	(0.26)

Appendix 13 Pearson's correlation matrix for the spatial distribution of dry deposits, dry nutrient deposits (kg 0.01 km^{-2}), and the inter-nutrient deposition correlations in November and December across the northern region of Ghana during the 2010-2011 Harmattan dry season. Values are coefficients, significant level (two-tail) in brackets. Significant ($P < 0.05$) correlations are defined by linear regressions presented in Table 5.5

	Ca	Mg	K	Na	Nitrate	Phosphate	Longitude	Latitude
				November				
Dust amount	**0.92	**0.97	**0.84	**0.77	0.42	**0.92	0.02	**0.72
	(0.00)	(0.00)	(0.00)	(0.00)	(0.13)	(0.00)	(0.95)	(0.00)
Ca	1	**0.93	**0.76	*0.53	0.41	*0.61	-0.13	*0.57
		(0.00)	(0.00)	(0.05)	(0.15)	(0.02)	(0.66)	(0.03)
Mg		1	**0.71	*0.68	0.38	*0.62	0.08	*0.63
			(0.00)	(0.01)	(0.18)	(0.02)	(0.79)	(0.02)
K			1	0.38	0.24	*0.66	-0.19	*0.67
				(0.17)	(0.41)	(0.01)	(0.51)	(0.01)
Na				1	0.19	*0.63	0.18	*0.62
					(0.51)	(0.02)	(0.54)	(0.02)
Nitrate					1	0.13	0.18	0.28
						(0.66)	(0.54)	(0.33)
Phosphate						1	-0.23	**0.74
							(0.43)	(0.00)
				December				
Dust amount	**0.76	**0.98	0.18	**0.86	0.07	0.28	0.17	**0.88
	(0.00)	(0.00)	(0.52)	(0.00)	(0.81)	(0.34)	(0.54)	(0.00)
Ca	1	**0.85	*0.63	*0.53	*0.62	0.14	0.05	*0.57
		(0.00)	(0.01)	(0.04)	(0.01)	(0.63)	(0.87)	(0.03)
Mg		1	0.28	*0.62	0.23	0.30	-0.07	**0.76
			(0.31)	(0.01)	(0.41)	(0.29)	(0.81)	(0.00)
K			1	0.23	**0.96	0.31	0.03	0.35
				(0.41)	(0.00)	(0.28)	(0.92)	(0.21)
Na				1	0.19	0.00	0.34	**0.72
					(0.50)	(0.99)	(0.21)	(0.00)
Nitrate					1	0.18	0.03	0.27
						(0.55)	(0.92)	(0.33)
Phosphate						1	-0.30	0.50
							(0.30)	(0.07)

Appendix 14 Pearson's correlation matrix for the spatial distribution of dry deposits, dry nutrient deposits (kg 0.01 km^{-2}), and the inter-nutrient deposition correlations in January and February across the northern region of Ghana during the 2010-2011 Harmattan dry season. Values are coefficients, significant level (two-tail) in brackets. Significant (P < 0.05) correlations are defined by linear regressions presented in Table 5.5

	Ca	Mg	K	Na	Nitrate	Phosphate	Longitude	Latitude
				January				
Dust amount	0.34	**0.91	**0.82	**0.76	0.07	*0.67	0.19	**0.81
	(0.21)	(0.00)	(0.00)	(0.00)	(0.79)	(0.01)	(0.50)	(0.00)
Ca	1	**0.85	0.21	-0.04	0.04	0.14	-0.28	0.38
		(0.00)	(0.45)	(0.89)	(0.88)	(0.63)	(0.31)	(0.17)
Mg		1	0.50	0.31	0.00	0.31	-0.04	*0.67
			(0.06)	(0.26)	(1.00)	(0.28)	(0.89)	(0.01)
K			1	*0.53	0.33	0.41	0.44	0.58
				(0.04)	(0.23)	(0.15)	(0.10)	(0.02)
Na				1	0.44	0.34	0.37	*0.57
					(0.10)	(0.24)	(0.17)	(0.03)
Nitrate					1	**0.87	-0.02	0.35
						(0.00)	(0.93)	(0.20)
Phosphate						1	-0.23	*0.70
							(0.44)	(0.01)
				February				
Dust amount	0.27	**0.96	**0.95	**0.92	**0.73	**0.89	0.49	*0.60
	(0.33)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.06)	(0.02)
Ca	1	*0.57	0.35	0.12	0.09	-0.19	0.00	0.28
		(0.03)	(0.21)	(0.67)	(0.75)	(0.49)	(1.00)	(0.32)
Mg		1	**0.83	**0.71	0.44	0.45	*0.51	*0.55
			(0.00)	(0.00)	(0.10)	(0.10)	(0.05)	(0.03)
K			1	**0.77	*0.57	*0.60	0.40	*0.66
				(0.00)	(0.03)	(0.02)	(0.14)	(0.01)
Na				1	**0.82	*0.62	0.32	**0.71
					(0.00)	(0.01)	(0.25)	(0.00)
Nitrate					1	0.47	-0.04	*0.66
						(0.08)	(0.88)	(0.01)
Phosphate						1	0.23	*0.57
							(0.41)	(0.03)

Appendix 15 Modelled linear regressions and model fit parameters for statistically correlated (P < 0.05) inter-nutrient dry depositions across the northern region of Ghana during the 2010 -2011 Harmattan dry season

Nutrients	Inter- nutrient relation	R	R^2	SEE	Sig. level
		November			
Ca vs Mg	Ca = 2.51Mg - 0.022	0.93	0.86	0.063	0.00
Ca vs K	K = 2.733Ca - 0.004	0.76	0.58	0.390	0.00
Mg vs K	K = 6.9Mg - 0.067	0.71	0.50	0.424	0.00
Phos vs Ca	Ca = 17Phos	0.61	0.37	0.132	0.02
Phos vs Mg	Mg = 6.4Phos	0.62	0.38	0.048	0.02
Phos vs K	K = 66.8Phos	0.66	0.44	0.450	0.01
		December			
Ca vs Mg	Ca = 2.247Mg	0.85	0.73	0.243	0.00
Ca vsK	Ca = 0.093K - 0.22	0.63	0.40	0.360	0.01
Ca vs Nitr	Ca = 0.082nitrate - 0.246	0.62	0.38	0.364	0.01
K vs Nitr	K = 0.861Nitrate	0.96	0.92	0.914	0.00
		January			
Ca vs Mg	Ca = 2.119Mg - 0.019	0.85	0.72	0.232	0.00
		February			
Ca vs Mg	Ca = 1.218Mg + 0.114	0.57	0.33	0.154	0.03
Mg vs K	K = 4.77Mg - 0.151	0.83	0.69	0.282	0.00
Nitr vsK	K = 6.469Nitrate	0.57	0.33	0.418	0.03
Phos vs K	K = 24Phos	0.60	0.37	0.406	0.02
		Total annual deposition			
Ca vs Mg	Ca = 1.969Mg	0.86	0.74	0.465	0.00
Ca vs K	K = 2.475Ca	0.6	0.36	3.056	0.02
Mg vs K	K = 5.246Mg	0.55	0.31	3.172	0.03
Nitr vs K	K = 0.333Nitrate	0.61	0.37	3.021	0.02

Phos = phosphate, Nitr = Nitrate. Monthly relations determined from statistically significant monthly correlations (Appendices 8 and 9). Total annual relations determined from statistically significant annual correlations (Table 5.3)

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