

# Forest fire and carbon emission from burnt tropical forest: The case study of *Afram Headwaters* Forest Reserve, Ghana

By

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# Abstract

Estimation of carbon emission from wildfires is crucial for improving our understanding of the climate and carbon cycle dynamics. Forest fires burn a variety of fuel depending on weather conditions and topography of the burnt area. This results in enormous spatial and temporal variations in burnt fuel, which are directly related to carbon emissions. Therefore, modelling fire behaviour accurately can give a good estimation of fire-induced carbon emission. This study aimed to model tropical forest fire behaviour and study the influence of forest condition, topography and weather on the severity of fire and consequently on carbon emission. Carbon emission was estimated using a combined approach involving state-of-the-art fire behaviour modelling and GIS/remote sensing techniques. Aboveground forest biomass/carbon stocks were estimated from three nested-circular plots (of horizontal radii 12.62m, 8m and 4m) using stratified random sampling from sixty locations in four cover types. Spatial data themes of DEM, aspect, slope, canopy cover, and fuel model were prepared and formatted in GIS along with weather and wind files to run FARSITE, fire behaviour model. The fire model simulated fire behaviour (spread and fireline intensity) in temporally and spatially explicit manner. Simulations using the standard fuel models underestimated the size of real burnt area for some cover types. Two custom fuel models developed in this study provided a better estimate of burnt area. Fire intensity was used to scale the fraction of biomass consumed during burning. Total C sequestered in living AGB amounted to 1,843.1Gg with an average density of  $103.2 \pm 26 \text{ Mg.ha}^{-1} \text{ C}$ . Natural forest cover was the most C-rich, holding 54.3% of total sequestered C. Total C emission estimated for the 2007 wildfire was 46.2Gg C. This is equivalent to 149.2 Gg of  $\text{CO}_2$  emission. Agro-forest cover type was the highest emitter of C estimated at 24.2Gg C or 52.3% of the total emission. On unit area basis, degraded forest being the highest emitter released  $7.6 \text{ Mg.ha}^{-1} \text{ C}$ . Overall, average emission of  $6.4 \text{ Mg.ha}^{-1} \text{ C}$  was estimated. This study has demonstrated that fire-induced C emissions in countries with less developed fire and emission monitoring systems can be estimated when Remote Sensing & GIS techniques are coupled with off-the-shelf fire behaviour models.

**Key words:** fire behaviour; FARSITE, fire-induced carbon emission, aboveground biomass

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# Dedication

I happily dedicate this piece of research to my sweet heart, Ms Eunice Opoku Kusi; my lovely kids, Nana Kwame Kusi Dwomoh and Nana Yaa Pokuah Dwomoh, for their patience, prayers, support and encouragement. You are my world!

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## List of abbreviations

AGB	Aboveground Biomass
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
C	Carbon
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
FM	Fuel model
FR	Forest Reserve
Gg	Giga gram
GIS	Geographic Information Systems
ha	Hectare
IPCC	Inter-governmental Panel on Climate Change
Mg	Mega gram
REDD	Reducing Emissions from Deforestation and Degradation
RMSE	Root Mean Square Error
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change



# 1. Introduction

## 1.1. Background

Tropical forests are a major reservoir of global terrestrial carbon, and thus play an essential role in the carbon cycle (Chambers *et al.*, 2007; Cramer *et al.*, 2004; Olander *et al.*, 2008). They host about 40% of terrestrial biomass and account for about 17% of the total land-based carbon stocks (Lucas *et al.* 2004 cited in Wang & Qi, 2008). However, the alarming rate of deforestation and degradation in recent decades is changing the status of tropical forests in the global carbon-climate regime. These cover changes ultimately result in carbon emission into the atmosphere, thereby distorting the balance and stability of the climate system. It is estimated that tropical forest cover changes currently account for 20 - 25% of all anthropogenic global carbon emissions (Gibbs *et al.*, 2007; Mollicone *et al.*, 2007; Olander *et al.*, 2008; Skutsch *et al.*, 2007). Various factors are responsible for forest cover changes in the tropics; key among them are natural and/or human-caused forest fire (Cochrane, 2003). However, fire does not only reduce the forest, but also implies that more carbon remain in the atmosphere because they are not sequestered. More importantly, large amounts of carbon held in the forest biomass are released into the atmosphere when the trees are burned.

Fire is an important regulatory factor in some ecosystems (Tacconi *et al.*, 2007). However, its frequent occurrence in tropical forest ecosystems becomes destructive. Fire results in major changes to the composition, structure and function of the forest ecosystem (Cochrane, 2003; Lavorel *et al.*, 2007). Not only is the vegetation transformed, but large quantities of biomass are lost (Hussin, pers. comm.). Reports indicate that the extent of global biomass burning has tremendously increased over the past century (UNEP, 2008). It is now recognized as a significant global source of atmospheric carbon emission (Palacios-Orueta *et al.*, 2005), contributing more than half of all the carbon released into the atmosphere (UNEP, 2008). It is further reported that, the highest proportion of global biomass burning occurs in the tropics (Dwyer *et al.*, 2000; Palacios-Orueta *et al.*, 2005; Smith *et al.*, 2005). Moreover, biomass burning releases more other greenhouse gases per carbon dioxide than consumption of fossil fuel (Christian *et al.*, 2003). Indeed, frequent biomass burning and high rates of deforestation have made the humid tropics a probable net source of carbon to the atmosphere (Ciais *et al.*, 1995 and Potter, 1999 cited in Potter *et al.*, 2001). Therefore, controlling or even preventing tropical forest fires will significantly reduce global carbon emissions. Unfortunately, Ghana's tropical forest is not spared from this phenomenon.

## 1.2. Problem statement and justification

Ghana's high forest zone was largely isolated from fire until the early 1980s when wildfire swept through most of the nation's forest. Since then wildfire has become a recurrent phenomenon and continue to plague large areas of the country's dwindling forest resources. Wildfire has thus become a major contributor to forest degradation and deforestation. Fire is indeed regarded the most important single threat to the integrity of Ghana's forests (Swaine *et al.*, 1997). FAO (2007) recognised damage from wildfire as a significant threat to sustainable forest management in Africa. Williams *et al.* (2007) emphasised that even though Africa's fossil fuel emissions are very low, its carbon emission due to fire and land use changes constitute a globally significant source.

Even though there has been extensive research on different aspects of tropical forestry, estimation of emissions from tropical forest fires remains unexplored (Cochrane, 2003). Tacconi *et al.*, (2007) identified that forest fire science in the developing world is under-developed, still in its infancy and with few research scientist. Indeed, despite the increasing role of wildfires to forest cover changes, and the consequent carbon release, emissions from this source has never been accounted for in Ghana's greenhouse gas inventories (E.P.A., 2000). Among the various wildfire studies in Ghana, none of them focused on carbon emission aspect of the phenomenon. However, quantifying gaseous emissions from fires constitute a significant concern within the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (Palacios-Orueta *et al.*, 2005). Estimation of fire-induced carbon emission from Ghana's tropical forest will make an essential contribution in addressing Ghana's commitment to the UNFCCC. More importantly, such a study offer significant input in the development of methodologies for the implementation of the Reducing Emissions from Deforestation and Degradation in developing countries (REDD) under the UNFCCC. It is particularly important for improving national carbon accounting; identification of potential areas for carbon credits under REDD, and for overall forest fire management in Ghana.

Lu *et al* (2006) contend that accurate estimation of carbon emission from wildfires is crucial for improving our understanding of the climate - carbon cycle interaction. Most studies on carbon emission from fire relied on average burned area, average biomass levels and estimates of fraction of biomass consumed during fire (Kasischke *et al.*, 2005). However, wildfires burn various types of fuel depending on weather conditions and topography of the burnt area (Berjak & Hearne, 2002; de Groot *et al.*, 2007; French *et al.*, 2004). This results in enormous spatial and temporal variations in burnt fuel, which are directly related to carbon emissions (de Groot, 2006a, 2006b; French *et al.*, 2004; Lu *et al.*, 2006). Therefore, modelling fire behaviour accurately can give a good estimation of carbon emission (Hussin, pers. comm.). Hence, this study integrated state-of-the-art fire behaviour modelling in a GIS environment for the estimation of fire-induced carbon emission.

### 1.3. Research objective

The main focus of this research was to model tropical forest fire behaviour and study the influence of forest condition, topography and weather on the severity of fire and consequently on carbon emission, using the 2007 wildfire in the study area as a case study.

#### 1.3.1. Specific objectives

The research goal was achieved through the following specific objectives:

1. To map the dominant forest vegetation types and determine their aboveground biomass stocks.
2. To estimate the aboveground carbon densities of the forest cover types; and the total sequestered carbon of the study area.
3. To model fire behaviour/fireline intensity for the 2007 wildfire in the study area using FARSITE fire behaviour model.
4. To validate FARSITE's results of burning with real burnt scar map.
5. To model fire-induced carbon emission from forest cover types under known fire weather conditions during the 2007 fires in the study area.

#### 1.4. Research questions

1. What are the forest cover types in the study area and their aboveground biomass stocks?
2. What are the aboveground carbon densities of the forest cover types; and the total sequestered carbon of the study area?
3. Which areas experienced the most intense fire under weather conditions during the March 2007 fire?
4. How accurate is FARSITE's simulation of burnt area?
5. What are the estimates of fire-induced carbon emitted from forest cover types and the overall emission during the March 2007 fire in the study area?
6. Which forest cover types emitted the most fire-induced carbon from the 2007 fires?

#### 1.5. Research approach

The study followed the approach shown in the conceptual diagram in Figure 1. It started with literature review on tropical forest cover changes and carbon emissions. Particular attention was given to fire as an agent of forest cover change in the tropics and its effects on atmospheric carbon emission. Existing methods of fire-induced carbon estimation were studied and gaps identified.

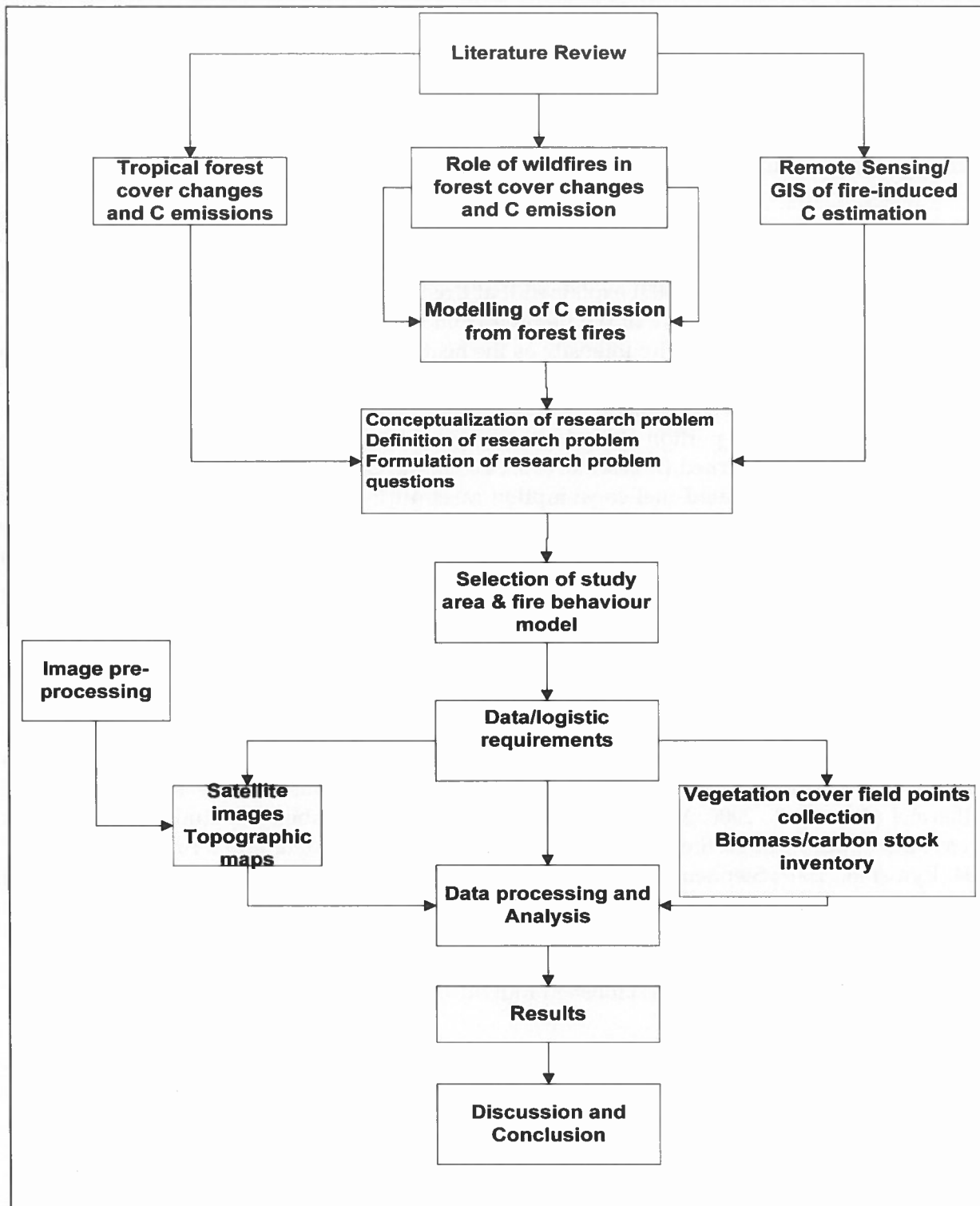


Figure 1: Conceptual framework of research approach

### 1.6. Fire behaviour modelling

Fire behaviour describes the manner in which fire reacts to the influences of fuel, weather, and topography. According to Arroyo *et al.* (2008) fire model refer to mathematical relationships describing potential characteristics of a fire. Yassemi *et al.* (2008) reported that fire behaviour models give numerical values for fire variables such as rate of spread, flame height, ignition risk or fuel consumption, all of which vary spatially and temporary. Advancement in computer

technology have lead to the development of spatially explicit fire behaviour simulation models capable of predicting fire spread and intensity across landscapes (Keane *et al.*, 2000). Simulation models in particular are useful for understanding the complexity of interacting factors influencing fire behaviour and their consequences on alternative management scenarios. Ryu *et al.* (2007) reported that modelling is an effective tool for characterising ecosystem dynamics over large temporal and spatial scales because they are cost-effective and non-destructive.

In order to determine fuel (biomass) consumption during fires and consequent emissions, understanding of fire characteristics including fire intensity and severity is essential. Neary *et al.*, 1999 (cited in Smith *et al.*, 2005) explained that fire intensity is a descriptor of fire behaviour as quantified by the temperature of the flaming front and the resulting heat energy produced. Other authors simply describe fire intensity as the heat energy released by a fire event per area over a period of time (J. N. Hall, 1991; Smirnova *et al.*, 2008). It is believed that higher intensities imply that more energy is available to burn more fuels, leading to increased carbon emissions. It has been stated that the portion of biomass consumed is related to the type or intensity of fire and the biomass being burned (Kasischke *et al.*, 2005). (de Groot, 2006a) reported on a range of fire intensities and associated fuel consumption rates during an experimental burning in Jack pine stands. Related to intensity is fire severity, which refers to a measure of fire effects described by the degree of mortality in aboveground vegetation or the degree of fire damage on the biophysical environment (Borchert & Odion, 1995; De Santis & Chuvieco, 2007; Smith *et al.*, 2005).

### 1.7. Fire area simulation model (FARSITE)

FARSITE is a biophysical, deterministic, two-dimensional, fire growth and behaviour simulation model (Carmel *et al.*, 2009; Finney, 2004; Stratton, 2004). The model which is spatially and temporally explicit is based on the physical statistical fire spread model of Rothermel (Arca *et al.*, 2006; Mbow *et al.*, 2004). Farsite has the ability to study fire behaviour across landscapes through the incorporation of different spatial data into a fire study (Finney, 2004; Ryu *et al.*, 2007; Stephens, 1998; Stratton, 2004, 2006). Ryu *et al.* (2007, citing Coen, 2003) expressed the need for models that can explicitly simulate forest fire with realistic fuel structure and atmospheric settings. Despite the long interest for ecological models to characterise fire at the landscape level, Finney (2004) reported that no model attempted to integrate the many aspects of fire behaviour already established individually.

FARSITE incorporates existing fire behaviour models of surface fire spread, crown fire spread, spotting, point-source fire acceleration, and fuel moisture (Finney, 2004; Mutlu *et al.*, 2008; Stratton, 2004, 2006); thereby allowing for the study of the connections between different fire behaviour models, implications of their assumptions, as well as identification of missing components among the various models (Finney, 2004). It has been found that cellular fire spread models are incapable of responding appropriately as environmental conditions become more heterogeneous (French, 1992 cited in Finney, 2004). Farsite overcomes this difficulty by using the vector or wave approach (Huygens' Principle) to calculate fire spread (Finney, 2004). It therefore has advantages over cellular models by providing a better reproduction of 2-dimensional fire growth patterns and a better response to wind speed and direction shift and fuel moisture change (Ryu *et al.*, 2007). Furthermore, the model is capable of predicting the fire behaviour of surface fire, crown fire and spotting, all of which interact with fuel moisture change (Finney, 2004).



The surface fire spread model in FARSITE is based on Rothermel's spread equation (Rothermel, 1972 cited in Finney, 2004) indicated in Equation 1.

$$R = \frac{I_R \xi (1 + \Phi_w + \Phi_s)}{\rho_b \varepsilon Q_{ig}}$$

**Equation 1: Rothermel's spread equation**

where:

$R$  = heading fire steady state spread rate ( $\text{m min}^{-1}$ )

$I_R$  = reaction intensity ( $\text{kJ min}^{-1} \text{m}^{-2}$ )

$\xi$  = the propagating flux ratio

$\rho_b$  = oven-dry bulk density,  $\text{kg m}^{-3}$

$\varepsilon$  = effective heating number, dimensionless

$Q_{ig}$  = heat of pre-ignition,  $\text{kJ kg}^{-1}$

$\Phi_w$  = wind coefficient

$\Phi_s$  = slope coefficient

According to Byram (Finney, 2004; Rothermel & Deeming, 1980), fireline intensity ( $I$ ), which describes the rate of energy released per unit length of the fire front ( $\text{kWm}^{-1}$ ) (Finney, 2004) is obtained by the equation:

$$I = hwR/60$$

**Equation 2: Byram's equation for calculating fireline intensity**

where  $h$  = heat yield of the fuel ( $\text{kJ kg}^{-1}$ ),

$w$  = weight of the fuel per unit area ( $\text{kg m}^{-2}$ ) burned in the flaming front,

$R/60$  = fire spread rate computed in units of  $\text{ms}^{-1}$

Finney (2004) explained that fire descriptors including fireline intensity and spread rate are dependent on the prevailing environmental conditions such as topography, fuel moisture, wind speed and direction.

## 2. Materials and Methods

### 2.1. Study Area

#### 2.1.1. Criteria for selection of study area

The area was selected because it met the following criteria: the area represents a typical tropical forest under threat of recurrent fire; availability of burnt area map to validate results of the model simulation; availability of maps and satellite images; permission granted to enter the reserve and the relative ease of accessibility. The area has an open canopy forest system largely presenting no problem with moisture dynamics under the canopy (Cochrane, pers. comm.). Furthermore the fire incidents are mostly slow-moving fires in the understory. Consequently, FARSITE was appropriate for the landscape.

#### 2.1.2. Location, extent and vegetation characteristics

The study was conducted at Afram Headwaters Forest Reserve (1°32'W - 1°48'W and 6°45'N - 7°25'N) located in Offinso Forest District in the Ashanti region of Ghana (Figure 2). Afram Headwaters Forest Reserve covers an area of 20,100 hectares (Hall and Swaine, 1981). The area is categorised under the Dry Semi-deciduous forest Fire Zone subtype (DSFZ). It is found within the forest-savanna transition zone of Ghana. It is characterised by sparse woody understory and well illuminated forest floor. Since the severe and extensive forest nationwide wildfires in 1983, the forest has been experiencing recurrent ground fires. These fires coupled with timber over-exploitation over the years have resulted in reduced stocking. The light canopy has permitted the increased presence of ground flora. These include dense weedy growth of species of *Marantaceae* and *Zingiberaceae* (Swaine *et al.*, 1997). Hall and Swaine (1981) recognised that deciduousness in the Fire Zone forest is the highest among all the forest types in Ghana.

The area represents one of the most fire-prone areas in Ghana's forest zone, characterised by frequent annual bushfires. Mohammed (2008) classified 37% of the study area as very high/high fire risk. About 48% of the area was reported burnt during a recent wildfire in March 2007 (Mohammed, 2008). Currently the area is mostly degraded. The present vegetation cover is mainly relics of the original forest, degraded portions, forest plantations of Teak (*Tectona grandis*) and agro-forests of the *Tuangya* system. Degraded conditions have favoured colonisation of large portions of the reserve by the non-indigenous woody invasive species *Broussonetia papyrifera* (Paper mulberry) (Bosu & Apetorgbor, 2007) and the 'Acheampong weed' (*Chromolaena odorata*). In particular *Chromolaena odorata* is highly combustible but regenerates strongly after fire (Swaine *et al.*, 1997).

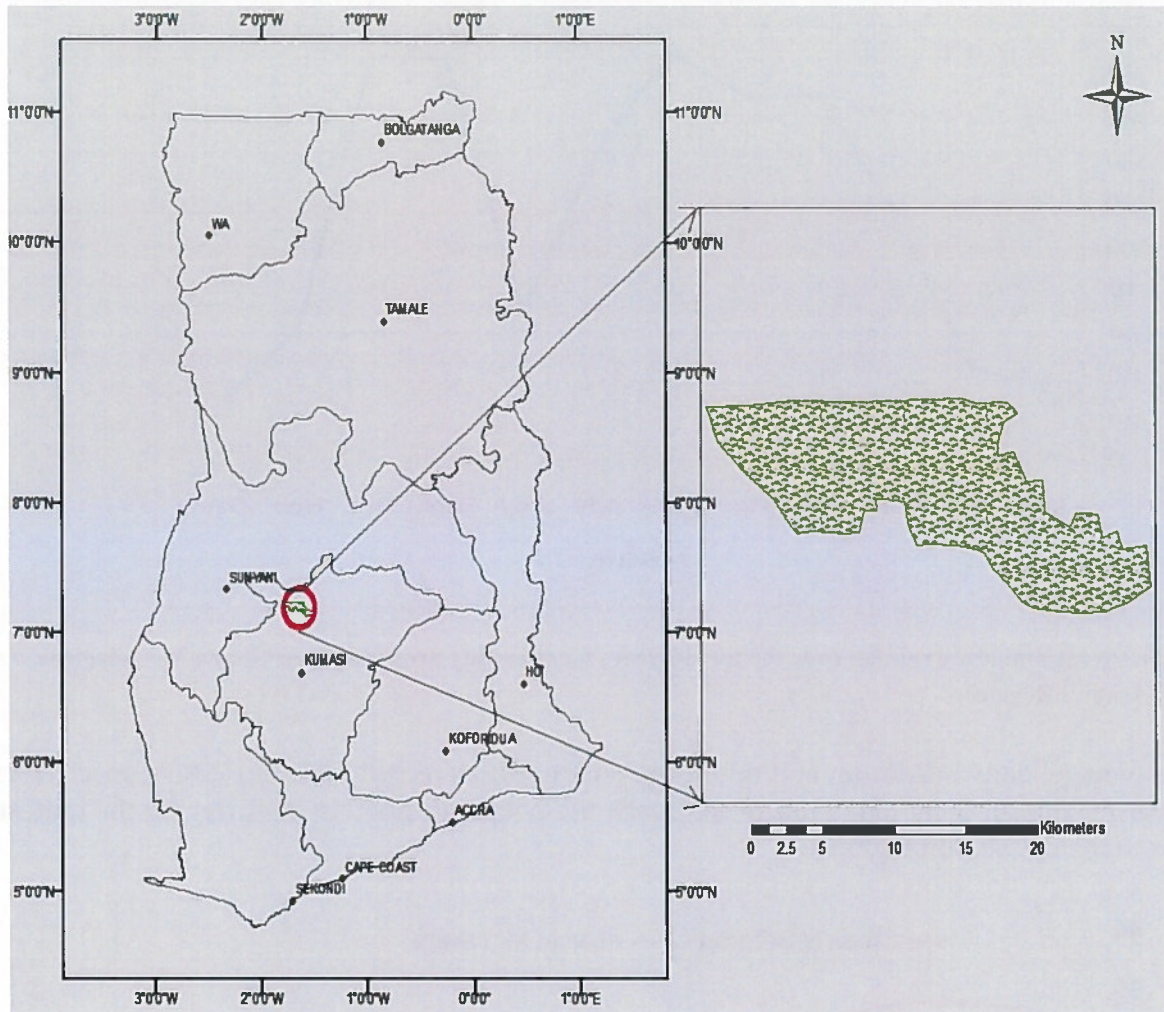


Figure 2: Map of Ghana showing location of the study area

### 2.1.3. Climate

The area experiences semi-equatorial and tropical conventional climates characterised by moderate to heavy rainfall (Offinso District Assembly, 2006). There are two distinct seasons, the rainy/wet (April – October) and the dry (November – March). The rainy season which is bimodal has the major season from April to July and the minor from September to mid November. Mean annual rainfall ranges 1,250 – 1,500 mm. Mean monthly rainfall ranges from below 30mm to about 200mm (Figure 3).

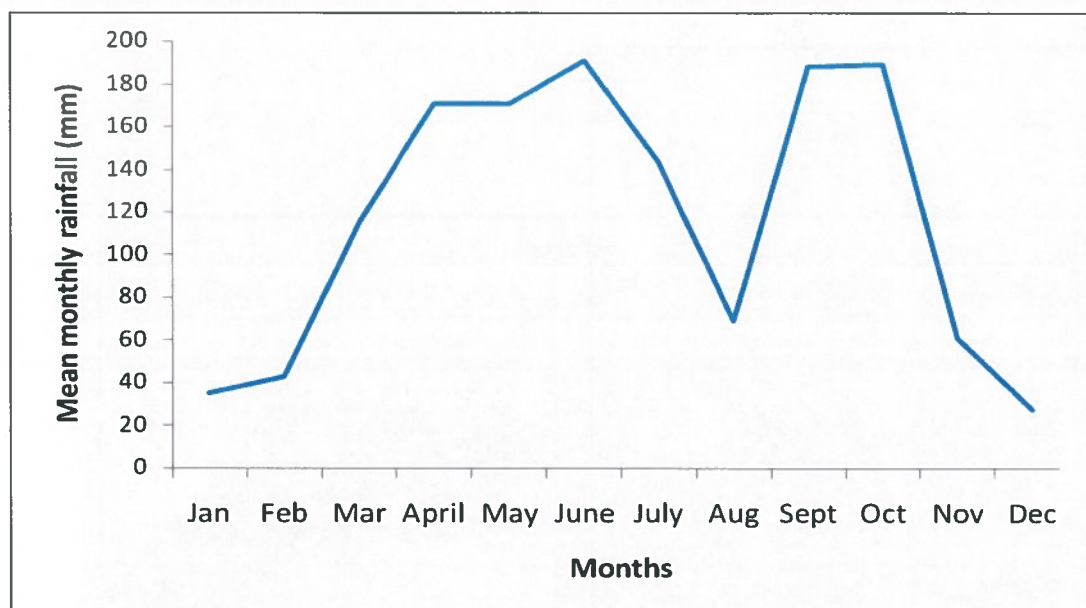


Figure 3: Average monthly rainfall over the last 10 years for the study area (Sources: Ghana Metrological Service, Ashanti Region)

On the average, daily maximum and minimum temperatures record 30°C and 22°C respectively. However maximum daily temperature can reach the neighbourhood of 35°C during the hottest months in the dry season Figure 4.

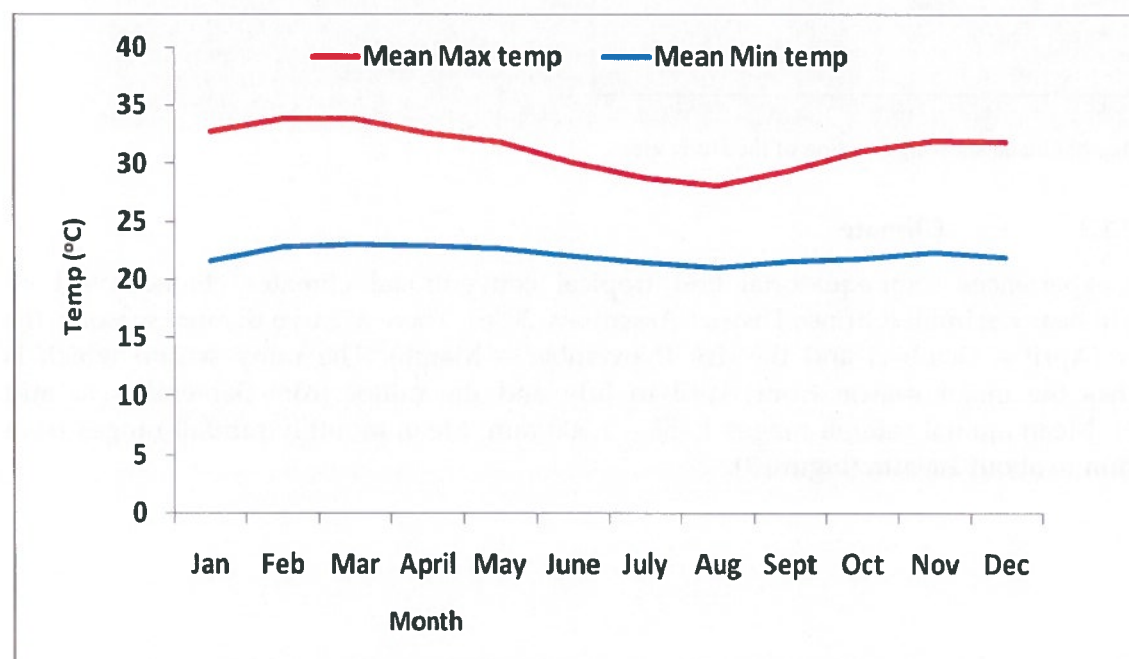


Figure 4: Mean daily minimum and maximum temperature in different months during the year

Relative humidity is generally high with an annual average of 80%. Pattern of maximum and minimum relative humidity are presented in Figure 5.



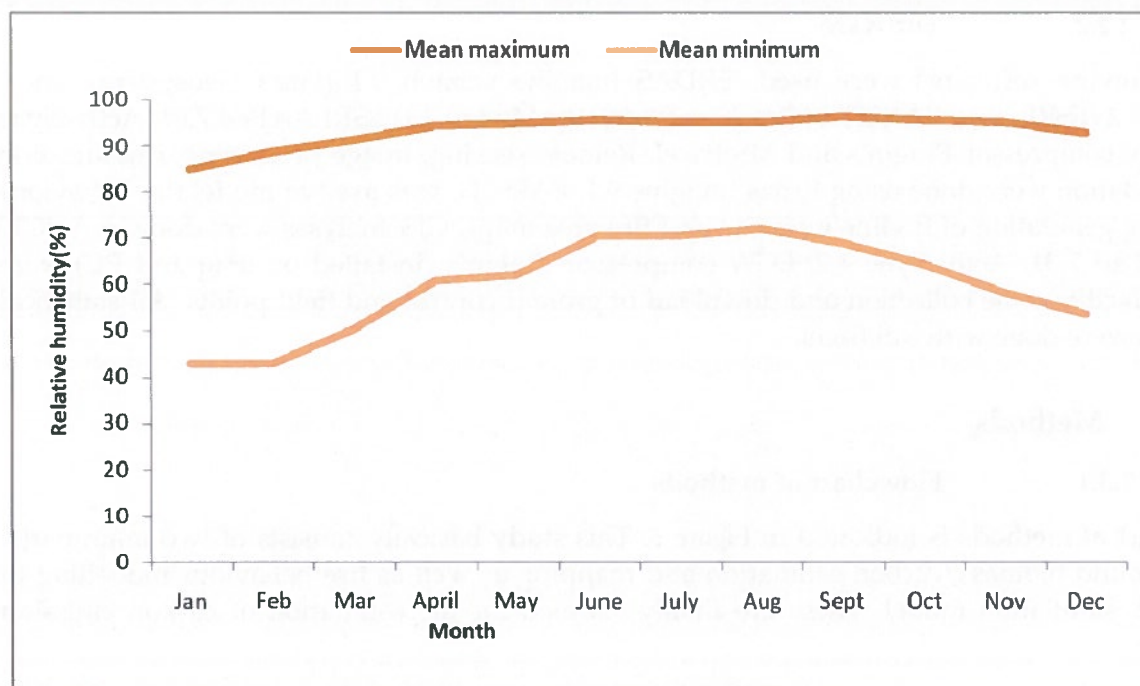


Figure 5: Average daily minimum and maximum relative humidity

The wind is south-westerly during the rainy season and north-easterly during the dry harmattan (Mohammed, 2008). Although the dry season spans November to March, the months of January, February and March have the highest probability of forest fires (Swaine *et al.*, 1997). Wildfires in the area are anthropogenic.

#### 2.1.4. Topography and drainage

The topography is generally flat or gently undulating (Offinso District Assembly, 2006). Altitude ranges from 300m to 410m above sea level. Limited areas of steep slopes occur in the eastern part of the reserve. The area is drained by two major streams: the *Afram* located in the east and *Brimu* found in the western part. Aside these there are a number of other water bodies that are largely ephemeral in nature.

## 2.2. Materials

### 2.2.1. Data

ASTER scene of the area taken on 24th February, 2008 was used for the study. The choice of the image was on the basis of availability and suitability. This image was used for the classification of forest cover types, and consequently for biomass/carbon distribution, canopy cover and fuel type maps. Burnt area map of 2007 produced by Mohammed (2008) was used to validate burnt area by the model simulation. Contour map generated from digitized topographic map was used to derive topographic variables (aspect, elevation and slope). Weather data were obtained from the Ashanti Regional Meteorological Service Department.

Topographic map and thematic maps of rivers and roads were loaded onto an iPAQ-GPS to facilitate the collection of ground control points for geo-referencing, image classification and validation.

### **2.2.2. Software**

The following softwares were used: ERDAS Imagine version 9.1 (Leica Geosystems, Inc.), ArcGIS 9.2 (ESRI, Inc.), FARSITE (Fire Area Simulator Model) 4.1, ESRI ArcPad 7.01, ActiveSync 4.2, ECW compressor Plugin's and MS Excel. Remote sensing, image processing, classification and validation were done using Erdas Imagine 9.1. FARSITE was used to model fire behaviour including generation of fireline intensity and fire area maps. GIS analyses were done in ArcGIS 9.2. ArcPad 7.01, ActiveSync 4.2, ECW compressor Plugin's (installed on iPaq and PC) were used to facilitate the collection and download of ground control and field points. All statistical analyses were done with MS Excel.

## **2.3. Methods**

### **2.3.1. Flowchart of methods**

Flowchart of methods is indicated in Figure 6. This study basically consists of two main parts: aboveground biomass/carbon estimation and mapping as well as fire behaviour modelling in FARSITE simulation model. These are finally coupled for the estimation of carbon emission from fire.



### 2.3.2. Image pre-processing

A level 1B ASTER image taken on 24<sup>th</sup> February, 2008 was imported into ERDAS Imagine 9.1. The image was geometrically corrected to the local coordinate system, the Transverse Mercator projection using the Accra datum. Geo-referencing was done by relating geo-reference tie points of the image to ground control points collected at road intersections and river confluences on the road and river maps. Geometric correction of the image was effected using second order polynomial transformation. A Root Mean Square Error (RMSE) of 0.10 pixel was obtained. Positional error of this magnitude is quite good since it is well below 0.5 of a pixel (Osei & Zhou, 2004).

Since the image used was a single date image, taken under clear skies with no cloud cover no atmospheric correction was performed.

### 2.3.3. Image classification

Digital image classification involves the process of categorizing pixels on an image to land cover classes (Jansen, 1996). According to Lillesand *et al.* (2003) the purpose of the process is to assign all pixels in a digital image to one of several land cover classes.

#### 2.3.3.1. Sampling of field points

Random sampling was used to collect ground truth data for image classification and accuracy assessment. Sample points were randomly taken from all classes on the map. At each sample point cover type was noted. GPS was used to capture coordinates of plot centres. Other spatial attributes including slope, aspect and elevation were also recorded. The field points were randomly divided into two sets: training sample and test sample datasets.

#### 2.3.3.2. Supervised classification

In ERDAS Imagine 9.1 a supervised image classification, using maximum likelihood algorithm, was used to classify the image into five cover classes. The classification was done using the training sample collected during field work. Lillesand *et al.* (2003) explained that due to inherent spectral variability encountered by classifiers, classified outputs often show a salt-and-pepper appearance. Consequently, a 3x3 majority filter was used to smooth out the 'salt and pepper' appearance from the classification results (Lillesand *et al.*, 2003).

#### 2.3.3.3. Accuracy assessment

A digital image classification is considered incomplete unless it is validated (Lillesand *et al.*, 2003). Foody (2002) stressed the importance of accuracy assessment of maps produced from remotely sensed data. The author emphasised that accuracy assessments do not only serve as guide to map's quality and fitness, but also necessary in understanding errors in classification and their implications (Foody, 2002). Accuracy of the forest cover map was assessed using 123 test sample points collected during field work. Classification error matrix indicating overall accuracy, producer's accuracy and user's accuracy were computed to evaluate the classification results. Kappa statistic ( $K_{HAT}$ ), which determines the extent to which classification results surpass random assignment of pixels, was also derived (Lillesand *et al.*, 2003).



#### 2.3.4. Biomass and carbon stock inventory

Sierra *et al.* (2007) emphasized the importance of estimating carbon stocks in tropical ecosystems in view of their role for understanding the global C cycle, for adoption of climate change mitigation measures, and the management of ecosystems for C sequestration. The importance of biomass to our understanding of the biosphere-atmosphere interactions is also highlighted by (Anaya *et al.*). Alamgir & Al-Amin (2008) stressed the importance of estimating forest carbon stocks because of their potential for both carbon sequestration and emission. The use of spectral vegetation indices has been largely successful in evaluating forest biomass stocks for some ecosystems. However this option was not used in this study due the problem of saturation in tropical forest ecosystems (Gibbs *et al.*, 2007).

##### *Sampling design*

In view of time and logistic constraints biomass inventory was restricted to aboveground biomass. This was defined to include aboveground live tree biomass and herbaceous plants (plants and litter). In this study, the limited resources was focussed on the aboveground living tree biomass because trees typically constitute the major pool, and are the most directly affected by forest loss (Gibbs *et al.*, 2007). Below ground biomass and dead woody components were not considered. Consequently, the emission estimates may be lower than the real emissions because emissions could come from these pools during fires.

Fieldwork was conducted in November, 2008. A stratified random sampling was used for the biomass inventory, and consequently the estimation of sequestered carbon. This was necessary to capture the variations between the different cover types. Recent land cover map of 2007 (Mohammed, 2008) was used to facilitate stratification of the study area. In all biomass inventory was conducted in 60 plots distributed in four dominant forest cover types.

To ensure adequate representation of trees of different diameter and age classes, three nested-circular plots (Brown, 1997; IPCC, 2003) of 500 square meter or horizontal radius 12.62m (larger plot), 8m (medium plot) and 4m (small plot) were adopted (Figure 7). Circular plots were employed because they are quick and easy to layout in the field. Additionally, enumeration of trees is less difficult than squared plots. Slope correction was effected in instances where slope was more than 5%. In each plot, all woody trees  $\geq 5\text{cm}$  diameter at breast height (dbh) were identified for species, measured for dbh and recorded. Specifically, trees  $>50\text{cm}$  dbh were inventoried in the larger plots. Trees 15-50cm dbh were measured in the 8m radius plots. Smaller diameter tree,  $\geq 5\text{cm}$  and  $<15\text{cm}$  dbh were enumerated in the smaller plots (4m radius). Diameter measurements were taken using vernier calliper and diameter tape. Spatial information, including coordinates, elevation and slope were recorded for each plot.

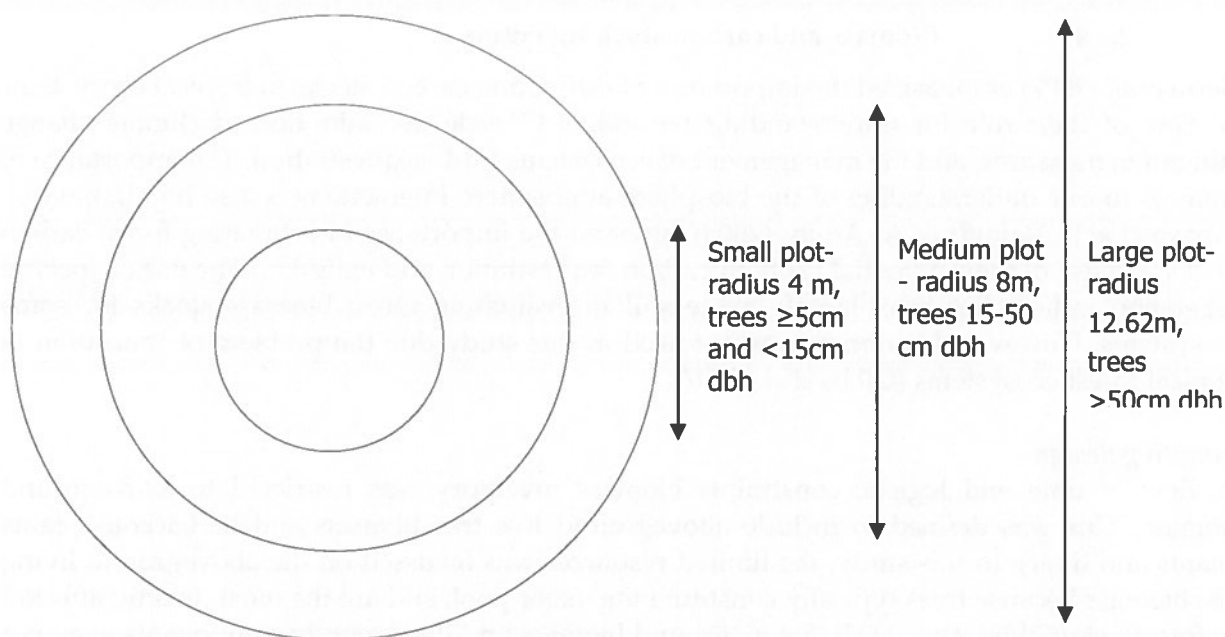


Figure 7: Schematic representation of sampling plot

#### ***Aboveground live tree biomass estimation***

IPCC grades highest locally developed biomass equations, as research indicate that equations developed elsewhere may result in very high errors (de Gier, personal communication). However, there is currently no local allometric equation developed for Ghana's forests. No attempt was made to develop one in the course of this research, as that is beyond the scope and resources of this thesis. Hence aboveground tree biomass was estimated using allometric equation for tropical dry forest (900-1500mm rainfall/year) recommended by Pearson *et al.* (2005) and Pearson & Brown (2004) shown in Equation 3. Similarly biomass of *Tectona grandis* in Teak plantations was estimated with Equation 4 suggested by IPCC (2003).

$$\text{Aboveground tree biomass (kg/tree)} Y = 0.2035 \cdot \text{DBH}^{2.3196}$$

Equation 3: Allometric equation for aboveground tree biomass

$$\text{Aboveground tree biomass (kg/tree)} Y \text{ of } Tectona \text{ grandis} = 0.153 \cdot \text{DBH}^{2.382}$$

Equation 4: Biomass equation for *Tectona grandis*

Where Y is the aboveground tree biomass in kg  
DBH is the measured tree diameter (in cm) at breast height (1.3m).

The biomass for each nested subplot was multiplied by expansion factors of 20, 50 and 199 respectively for the large, intermediate and small plots to obtain the biomass per hectare for each subplot. The biomass densities of the three nested subplots were summed up to get the total estimated tree biomass (kg.ha<sup>-1</sup>) for that plot location.

### Non-tree vegetation carbon pool

For the estimation of biomass in non-tree pools destructive sampling technique was used. Two small squared subplots of size 0.25m<sup>2</sup> (0.5m x 0.5m) were established in each plot location for sampling of herbaceous biomass (plant and litter) (IPCC, 2003). In each subplot all non-tree pools were clipped at ground level, collected and weighed for fresh weight. A well-mixed subsample were weighed (subsample fresh mass) from each sample and oven dried to a constant mass (subsample dry mass) at 100°C for 48 hours in the lab. Dry-to-wet mass ratios were determined for the subsamples. These ratios were used to convert the entire sample to oven-dry matter (Cummings *et al.*, 2002).

Following Cummings *et al.*, (2002) and Pearson & Brown (2004), the dry mass of the samples (from which subsample were oven-dried) were computed as

$$\text{Dry mass} = \frac{\text{subsample dry mass}}{\text{subsample fresh mass}} * \text{fresh mass of whole sample}$$

Equation 5: Estimation of non-tree vegetation biomass

The dry mass calculated for a particular non-tree vegetation pool was extrapolated to obtain the biomass density (Mg.ha<sup>-1</sup>) for that pool. Hence the sum of biomass densities of non-tree vegetation pools yielded the non-tree component biomass density for that plot.

### Total Carbon stocks

The plot tree biomass density values were converted to tree carbon stock (kg.ha<sup>-1</sup>C) by multiplication with carbon fraction of biomass. A biomass-to-carbon conversion factor of 0.5 (Gibbs *et al.*, 2007; IPCC, 2003; Nascimento & Laurance, 2002; Pearson & Brown, 2004)) was used. The same conversion factor was used to obtain the carbon densities (Mg.ha<sup>-1</sup>C) of the non-tree vegetation pools (Pearson & Brown, 2004). Finally the carbon density for each plot was obtained by summing up all carbon densities (for trees and non-tree components) for each plot location.

The mean carbon density per cover type was obtained by averaging the carbon densities of all sample plots in a particular cover type. Consequently, the total sequestered carbon per cover type was estimated by multiplying its average carbon density with total area of that cover type. Therefore, the overall sequestered carbon of the study area was computed by summing the total sequestered carbon of the different cover types.

#### 2.3.4.1. Map of sequestered carbon

In order to show the spatial distribution of sequestered carbon the vegetation cover map was reclassified and each cover type assigned its respective carbon density.

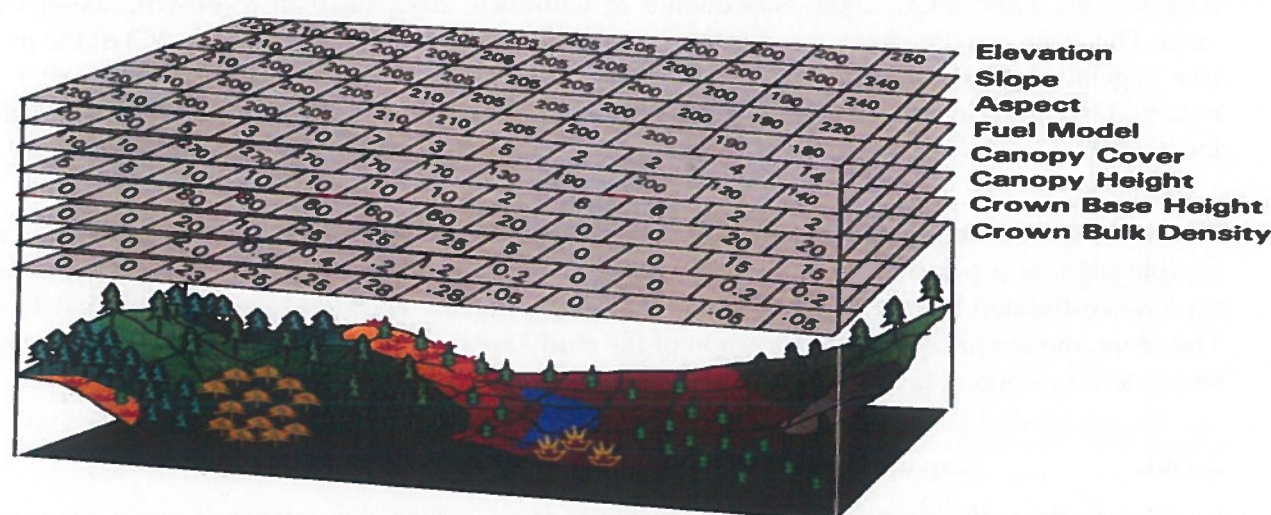
#### 2.3.5. FARSITE input layers

FARSITE requires five spatial raster input layers on the landscape: fuel model, canopy cover percentage, elevation, slope and aspect (Carmel *et al.*, 2009; Dasgupta *et al.*, 2007; Finney, 2004; Ryu *et al.*, 2007; Stratton, 2004, 2006). Other non-spatial inputs include daily records of maximum and minimum temperature and relative humidity, precipitation, cloud cover, latitude of the region and the dates for the simulation (Dasgupta *et al.*, 2007). Table 1 contains the list of inputs used to run the model. Schematic representation of the landscape files is shown in Figure 8.

**Table 1: Inputs used in FARSITE simulation**

Input type	Input	Usage
Landscape (GIS layers)	Latitude	Along with slope and aspect for determining angle of incident solar radiation
	Canopy cover map	Used to determine shading of surface fuels which influence fuel moisture computations and wind reduction
	Fuel map	Describes the surface fuel complex
	Vegetation map	Describes the vegetation cover
	Elevation map	For adiabatic adjustment of temperature and humidity
	Slope map	For computation of direct effect of fire spread
	Aspect map	Together with slope and latitude to determine angle of incident solar radiation
Climate	Temperature	Influences fuel moisture
	Wind speed and direction	Influence fire spread
	Relative humidity	Affects moisture conditions and rate of spread
	Precipitation	

Adopted and modified from Carmel *et al.* (2009) and Finney (2004)



**Figure 8: Raster landscape input layers required from GIS for FARSITE simulation (Source: Finney, 2004)**

### 2.3.5.1. Canopy cover

During the biomass inventory (section 2.3.4 above) canopy cover percentage was determined for each plot location using a hemispherical densiometer. Within each plot five readings in different directions (N, S, E, W and centre) were taken and averaged for that plot. This was done to reduce bias. The readings were averaged per cover and the values assigned to their respective cover classes. The canopy cover layer was obtained by reclassifying the cover map (Mbow *et al.*, 2004).



Shrub cover and herb cover percentages were visually estimated (Falkowski *et al.*, 2005) for each sample plot. These were determined in 5m x 5m and 3m x 3m plots located at the centre of each plot for shrubs and herbs respectively.

### 2.3.5.2. Fuel models

#### *Standard fuel models*

A fuel model refers the numerical description of the physical parameters characterising each fuel type (Arroyo *et al.*, 2008). Fire spread and behaviour models require appropriate fuel models (Arroyo *et al.*, 2008; Cochrane, 2003)). The choice of fuel model constitutes an important aspect in fire behaviour modelling, since it directly affects simulation results. Such fuel models have been characterized for various ecosystems and forest types but not for tropical forests (Cochrane, 2003). Therefore standard fuel models of Anderson (1982) and Scott & Burgan (2005) which exist in FARSITE were initially adopted. Mbow *et al.* (2004) who used FARSITE in neighbouring Senegal assigned vegetation classes to the 13 fuel models developed by Anderson (1982). In this study appropriate numbers of these standard models were matched to vegetation types and tested. Models which closely represent characteristic cover types and fire spread were selected. Consequently, the forest cover map was reclassified and each cover type assigned their respective fuel model (Table 2) to obtain the fuel model map (Falkowski *et al.*, 2005; Keane *et al.*, 2000; Mbow *et al.*, 2004).

**Table 2: Cover types and corresponding standard fuel models used in this study**

Cover type	Fuel model code
Natural Forest	10
Plantation	9
Agro-forest	5
Degraded forest	4
Bare ground	99

#### *Custom fuel models*

During this study two custom fuel models were developed to reflect cover types not well represented by the standard fuel models in FARSITE. Fuel parameterization for tropical forest is difficult because data hardly exist. The only available data for the tropics that closely resemble conditions at the study area was gathered from the Photo Series publication for the Cerrado ecosystems in central Brazil (Ottmar *et al.*, 2001). This publication was personally obtained from the Fire and Environmental Research and Applications Team (FERA), USDA Forest Service (courtesy Dr. Ottmar). Few other parameters including surface-to-volume ratio (SAV) and heat content of fuels were adopted from Scott & Burgan (2005). Saturation point of cellulosic material is about 30%; hence this value was used as the moisture of extinction (Alvarado, pers. comm.). Selection of parameters was guided by field observations. Key parameters used in constructing the custom fuel models are listed in Table 3.

**Table 3: Parameters used in developing custom fuel model for the study area**

Cover type	Fuel model code	Fuel parameters					
		Fuel loading (Mg.ha <sup>-1</sup> )				Fuel depth (ft)	Moisture of extinction (%)
		1hr	10hr	100hr	Herb		
Degraded forest	14	3.44	2.97	0.86	2.92	0.5	30
Agro-forest	15	1.32	3.29	0.46	2.05	0.3	30

Data source: (Ottmar *et al.*, 2001; Scott & Burgan, 2005)

The custom fuel models developed were tested in multiple runs and a representative output compared with real fire map and burnt area from standard fuel models.

### 2.3.5.3. Topographic data

Digital elevation model (DEM) was derived by interpolation of contour lines using the spatial analyst tool in ArcGIS version 9.2 (ESRI Inc.). In FARSITE all raster data inputs are required to be of the same spatial resolution (Finney, 2004). For this reason the DEM was resampled to 15m resolution (of the ASTER image) using nearest neighbour algorithm in ArcGIS version 9.2 (ESRI Inc.). The 15 meter resolution used in this study was appropriate to provide an acceptable level of detail depicting variation in the landscape of the study area. Slope and aspect maps were subsequently generated from the DEM.

### 2.3.5.4. Climatic data

The climatic data used for FARSITE simulation involved weather and wind data. These were: daily minimum and maximum temperature, relative humidity and precipitation, as well as wind speed and direction. Daily wind speed was based on the arithmetic mean of synoptic observations taken. Climatic data were collected from the nearest weather station to the study area.

Percentile weather data were run to examine the effect of three weather scenarios on fire intensity. Values for the weather scenarios area presented in Table 4. The scenarios were: the 75<sup>th</sup>, 85<sup>th</sup> and 95<sup>th</sup> percentile weather conditions during the fire season. Thus these weather conditions are only exceeded 25%, 15% and 5% of the time, respectively.

Table 4: Weather information for the 75th, 85th and 95th percentile

Weather variable	75th	85th	95th
Maximum temperature °C	34	35	36
Minimum temperature °C	24	24	25
Wind speed	7	7	9
Relative humidity (minimum)	94	95	97
Relative humidity (maximum)	56	58	62
Wind direction (degrees from North)	180	180	180

(Source: Metrological Service, Ashanti region)

### 2.3.6. Fire behaviour simulation

The vegetation and topography datasets were transformed to FARSITE input formats. The data processing was done using ArcGIS version 9.2 (ESRI Inc.). All the layers were converted to ASCII grid files and integrated into the development and running of the model. Weather data were input as text stream. The simulation duration was three days, 7 – 9 March, 2007. This date correspond to days on which fire was reported to have occurred in the area. The year 2007 was selected because it was a typical fire year, for which burnt area map was available for model validation.

Ignition points were randomly located at high ignition risk areas identified by Mohammed (2008) in fire risk model developed for study area. Time step of model simulation was set to 30 minutes. Perimeter and distance resolutions were both set to 30 and 60 meters respectively. All raster simulation results were output to the original image resolution of 15 metres.

The same model parameters were used to simulate fire behaviour in both the standard and the custom fuel models.

### 2.3.7. Fire-induced carbon emission modelling

The total carbon released ( $C_t$ ) from burning of biomass was estimated using the equation by Seiler & Crutzen (1980).

$$C_t = ABfc\beta$$

**Equation 6: Equation for estimation of C emission from fire**

Where  $A$  is the area burnt (ha, from burnt area map),  $B$  is the biomass density ( $\text{Mg}\cdot\text{ha}^{-1}$  from field biomass data),  $fc$  is the carbon fraction of the biomass (0.5), and  $\beta$  is the fraction of biomass consumed or combustion efficiency during biomass burning.

This equation was adopted because only aboveground biomass was considered in this study. However the biomass density was defined to constitute the biomass that is available to burn. This is further explained elsewhere in this section.

As noted by Kasischke *et al.* (2005),  $\beta$  which is a scaling factor for the biomass fraction consumed, is related to the type or intensity of the fire and the biomass being burned. To obtain intensity, FARSITE's fireline intensity output from a run with custom fuel models was imported and processed in ArcGIS 9.2 (ESRI, Inc.) and ERDAS Imagine version 9.1 (Leica Geosystems, Inc.). Intensity from custom models was chosen because it gave better representation of fire

behaviour than the standard models. The fireline intensity raster map was scaled zero to one (0 – 1: low - high), to reflect the fraction of biomass consumed during fire. It was assumed that high intensity fires lead to higher biomass consumption. This is because at higher intensities more energy is available to burn more fuel at the flaming front. Kasischke & Bruhwiler (2003) and Tan *et al.* (2007) determined fractions of biomass consumed during fire by categorizing burn severity into classes and assigning different fractions of biomass to each class.

#### *Aboveground biomass available for burning*

Palacios-Orueta *et al.* (2005) stressed the need to characterize available fuel in biomass consumption studies, because not all the biomass in an ecosystem is available for burning. The authors indicate that total biomass is only consumed when an extraordinarily intense fire occurs. Considering the climatic and vegetation characteristics of the study area, it is highly unlikely that all the biomass can burn within a single fire event. The amount of biomass available for burning is influenced by stand structure and fuel's physical characteristics, including distribution of fuel size classes. Kasischke *et al.* (2005) explained that shrubs have higher biomass available for burning than large trees. These authors further stated that as trees grow bigger more biomass are allocated in the trunk and large branches, hence the amount of biomass available for burning (located in branches and foliage) decreases. Indeed the amount of combustible fine fuels decrease as biomass increases (Kasischke *et al.*, 2005). In order to account for such variations, Kasischke *et al.* (2005) made the following assumptions on burning of aboveground biomass in their studies: areas with

- low total AGB, 80% of the AGB was available to burn;
- moderate levels of aboveground biomass, 50% available to burn;
- high AGB, 35% was available to burn.

Since data on available fuel do not exist for the study area, similar assumptions were adapted in this study (Table 5).

**Table 5: Assumptions on level of AGB available for burning**

Level of AGB (Mg.ha <sup>-1</sup> )		Biomass available to burn (%)	Cover types included
Low	< 150	80	Degraded forest, Agro-forest
Moderate	150 -250	50	Plantation
High	>250	35	Natural forest

Adapted from (Kasischke *et al.*, 2005)

Based on these assumptions estimates of biomass available for burning were made from the field biomass inventory data (Table 9).

Therefore to obtain the carbon lost during the 2007 fires, the real burnt area map of 2007 was crossed with the vegetation cover map to determine the area burnt per cover type.  $\beta$  was obtained from fire intensity for the burning period, B from the field biomass data, and Equation 6 was applied.

#### **2.3.8. Model validation**

Historic database for validating model results of emissions was not available. Moreover, setting of fire for model evaluation was not possible during this work; since fire is strictly prohibited in



the study area. As a result only burnt area simulation results were evaluated. Historic burnt area map was only available for March 2007 (Mohammed, 2008). Therefore the model outputs with weather data corresponding to the reported burning period were evaluated. The burnt area map was obtained from Mohammed (2008), who produced the burnt scar map of the study area from ASTER (Li *et al.*, 2000). The map had already been validated and yielded good accuracy (84%) (Mohammed, 2008).

During the validation process the burnt area from model simulation was vectorized and cross analysed with the real burnt area map in ArcGIS 9.2. Proportions of the burnt area by simulation were computed and compared with real burnt area in different cover types. Similar procedure was followed to validate simulation results using the custom fuel models.

### 3. Results

#### 3.1. Dominant vegetation cover types and their aboveground biomass

##### 3.1.1. Classification of dominant vegetation cover types

Five cover types were realised from the supervised classification of the study area (Figure 9). These were natural forest, agro-forest, plantation forest, degraded forest and non-vegetated/bare ground. Description of the cover types are briefly presented in Table 6.

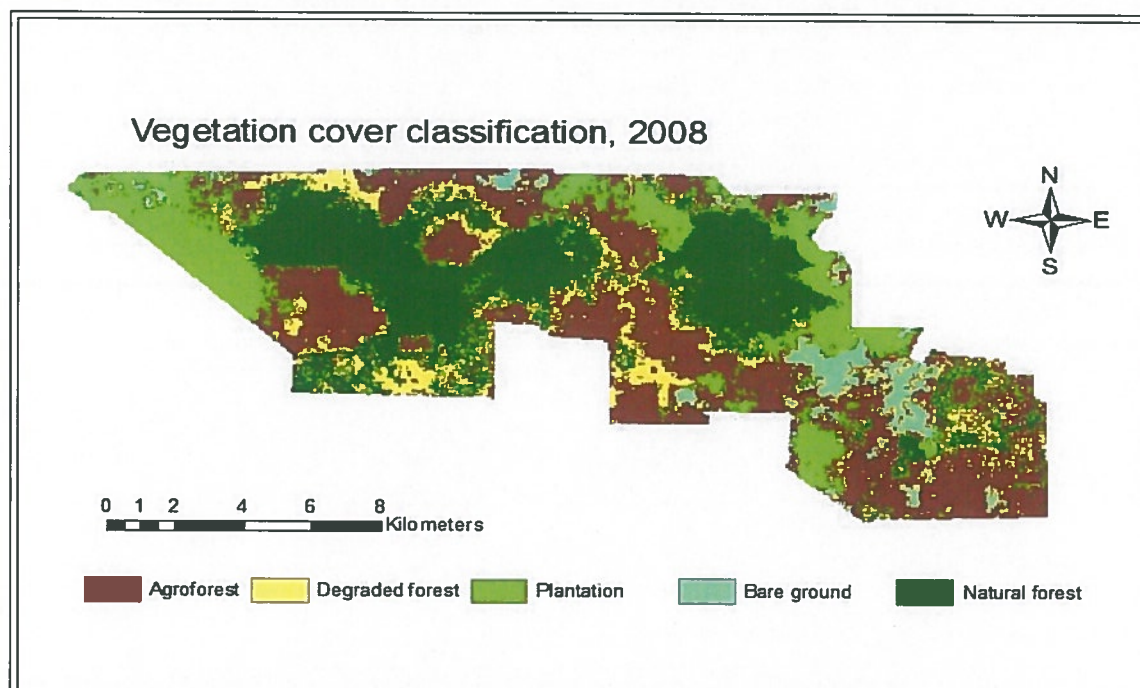


Figure 9: Classified land cover map 2008 of Afram Headwaters Forest Reserve

Table 6: Brief description of the dominant cover types in Afram Headwaters Forest Reserve

Cover type	Description
Natural Forest	Forested areas showing characteristics of the original natural vegetation cover of mixed tree species
Plantation	Forest plantations made up of Teak monoculture
Agroforest/Farm	Young forest plantations of 1-4 years, interplanted with food crops through the <i>Taungya</i> system. Large areas are invaded by grasses and other weeds.
Degraded forest	Degraded forest portions with isolated trees and low canopy cover. Most areas are occupied by the invasive tree species <i>Broussonetia papyrifera</i> . The shrub layer is dominated by the highly combustible invasive shrub <i>Chromolaena odorata</i> . Grasses such as <i>Pennisetum spp.</i> , <i>Panicum maximum</i> are present.
Bare ground	Includes areas of exposed soil surface, settlements and rocky areas

As indicated in Table 8 (below) and Figure 10, agro-forest covering 5,794 ha was the most predominant cover type in the study area. It constituted 32.9% of the total area of 17,626 ha. Natural forest of total size 5,724 ha forming 32.5% of the entire area was the second largest cover type identified. This was followed by forest plantation which covered an area 3,446 ha (19.5%). Degraded forest measuring 1,808 ha with 10.3% coverage was the fourth largest cover type. Non-vegetated/ bare ground comprising barren land, settlements, rocky and denuded areas was the category with the least area coverage. This formed 4.8% of the area translated as 854 ha.

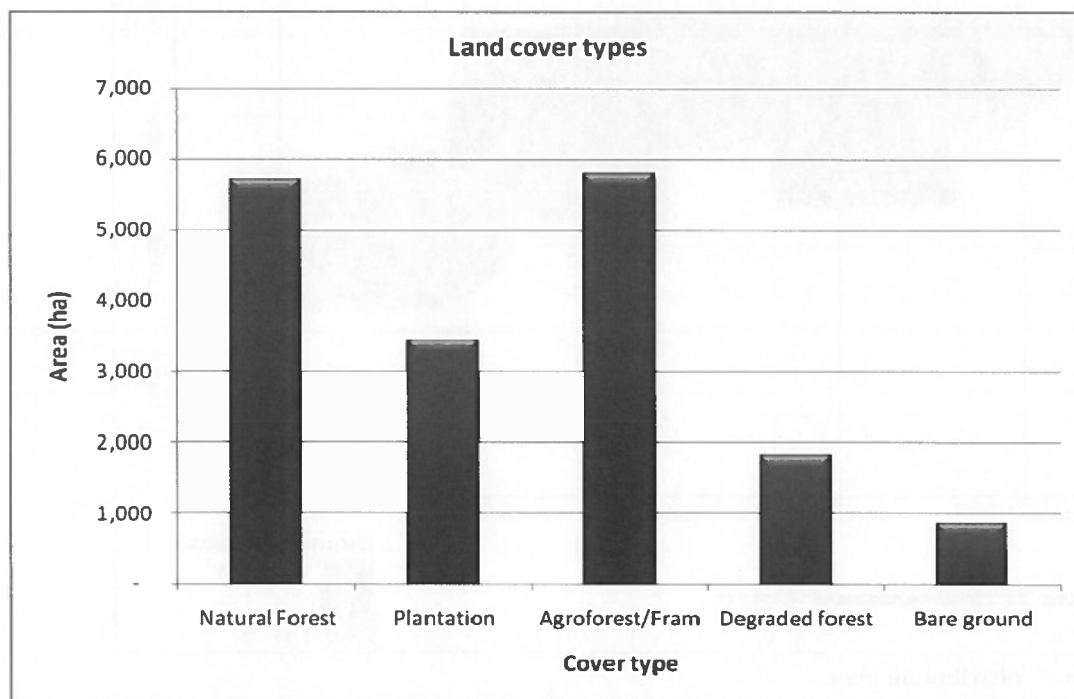


Figure 10: Distribution of cover types in the study area

### 3.1.2. Accuracy assessment of classification

Overall classification accuracy and Kappa statistic ( $K_{HAT}$ ) of 78.1% and 0.72 respectively were obtained for the vegetation cover mapping. Classification error matrix indicating these indices as well as producer's accuracy and user's accuracy are shown in Table 7.

Table 7: Classification accuracy report

Class Name	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy	Kappa
Forest	41	35	32	78.05%	91.43%	0.87
Plantation	27	31	23	85.19%	74.19%	0.67
Agro-forest/Farm	20	28	16	80.00%	57.14%	0.49
Degraded forest	24	20	16	66.67%	80.00%	0.75
Bare	11	9	9	81.82%	100.00%	1.00
Totals	123	123	96			
Overall Classification Accuracy				78.1%		
Overall Kappa Statistics				0.72		

## 3.1.3. Aboveground biomass in cover types

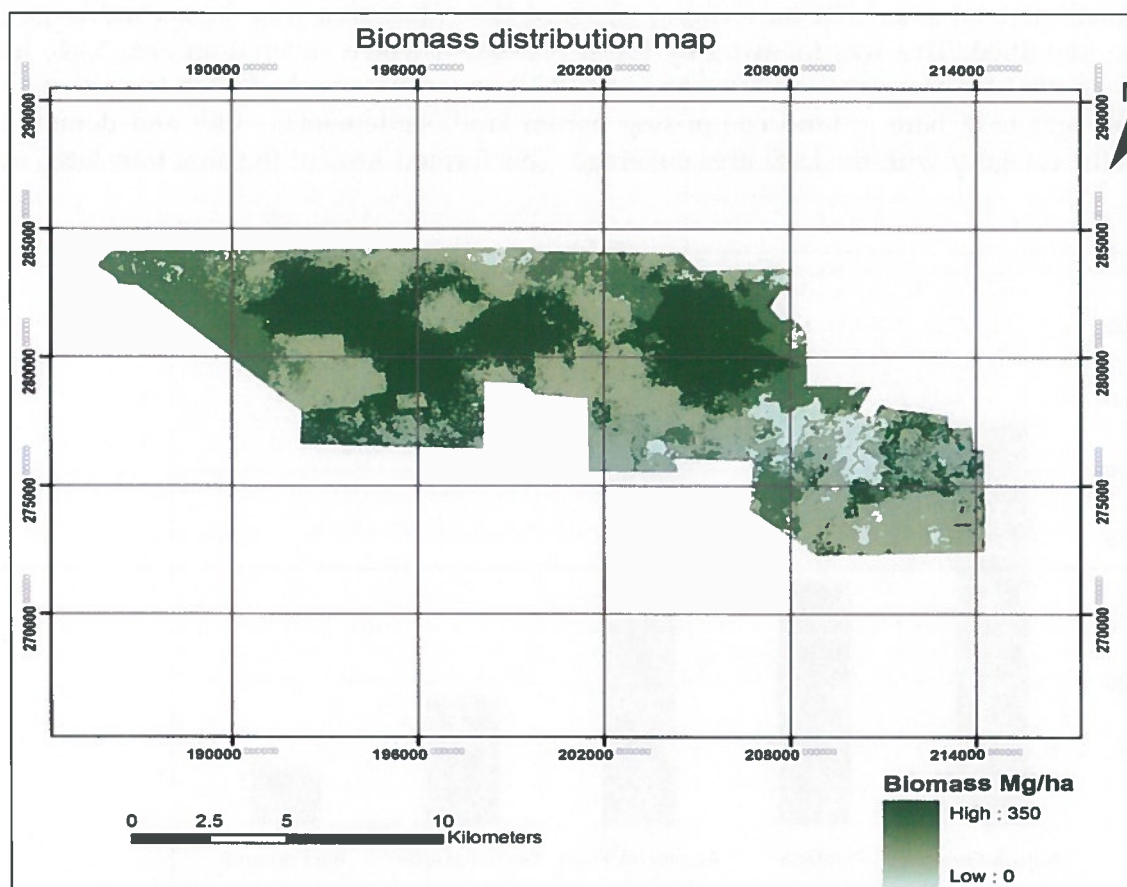


Figure 11: Biomass distribution map

Spatial distribution of biomass in the study area is shown by the map in Figure 11. Aboveground biomass (AGB) density in the study area ranged between 107.8 – 349.6 Mg.ha<sup>-1</sup> (Table 8). This was true for the four forest cover types. The AGB of non-vegetated areas was assumed to be zero. Overall mean density of  $206.5 \pm 52$  Mg.ha<sup>-1</sup> (mean  $\pm$  standard deviation) was estimated for the entire study area. Natural forest with 349.6 Mg.ha<sup>-1</sup> registered the highest biomass density. This was followed by plantation forest with a density of 240.8 Mg.ha<sup>-1</sup>. Degraded forest, being the third biomass-rich cover, contained 127.8 Mg.ha<sup>-1</sup>. Agro-forest contained the least biomass per unit area, viz. 107.8 Mg.ha<sup>-1</sup> (Table 8).

Table 8: Forest cover types and living aboveground biomass stocks

Cover type	Area (ha)	Percent area (%)	Mean AGB* (Mg.ha <sup>-1</sup> )	Total AGB* (G g)	Percentage of total biomass (%)
Natural forest	5,724	32.5	349.6	2,001.2	54.3
Plantation	3,446	19.5	240.8	829.6	22.5
Agro-forest	5,794	32.9	107.8	624.4	16.9
Degraded forest	1,808	10.3	127.8	231.1	6.3
Bare ground	854	4.8	-	-	-
Total area	17,626	100		3,686	100

\*AGB = aboveground biomass

On the whole, the *Afram Headwaters* Forest Reserve was estimated to contain 3,686 G g (approximately 3.7 T g) of dry aboveground forest biomass. In terms of distribution, natural forest alone hosted 2,001.2 G g (2 T g) or 54.3% of the total biomass estimate (Table 8). Forest plantation which recorded the second largest amount contained 22.5% or 829.6 G g (0.83 T g) of biomass. Agro-forest and degraded forest respectively held 624.4 G g and 231.1 G g. These represents 16.9% and 6.3% respectively, of the total aboveground biomass in the study site. Aboveground biomass quantities with respect to different cover types are depicted by Figure 12.

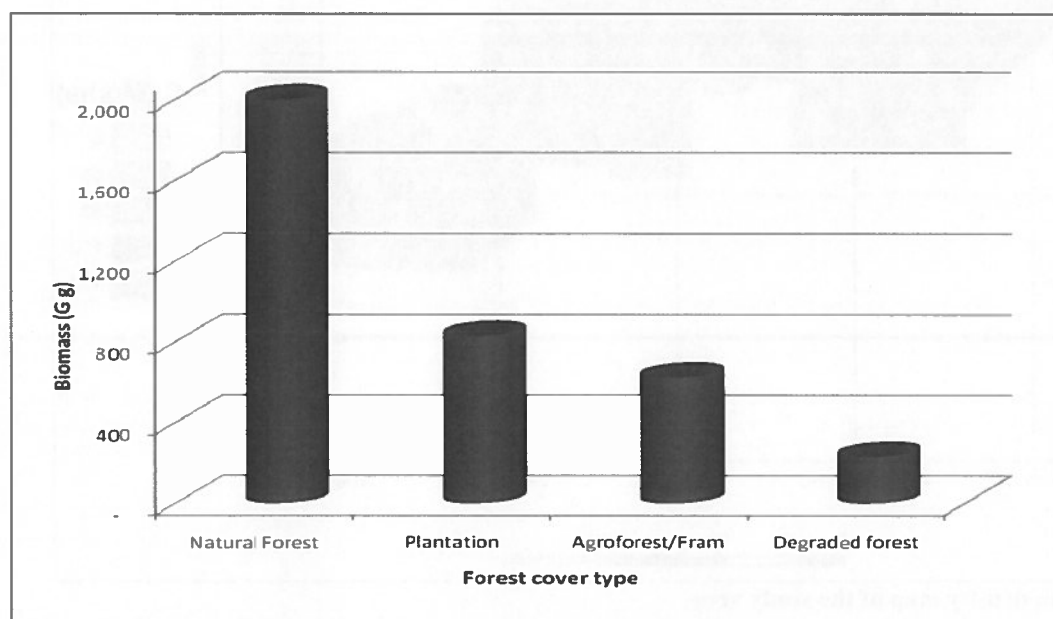


Figure 12: Distribution of aboveground biomass in the cover types

Table 9 below indicates estimates of the amount of biomass available as fuel based on assumptions made in section 2.3.7.

Table 9: Estimates of AGB available for burning

Cover type	AGB density (Mg ha <sup>-1</sup> )	AGB available for burning
Natural forest	350	122
Plantation	241	120
Agro-forest	108	86
Degraded forest	128	102
Bare ground	0	0

### 3.2. Aboveground carbon densities and total sequestered carbon

Spatial distribution of mean carbon density of the cover types have been mapped in Figure 13.



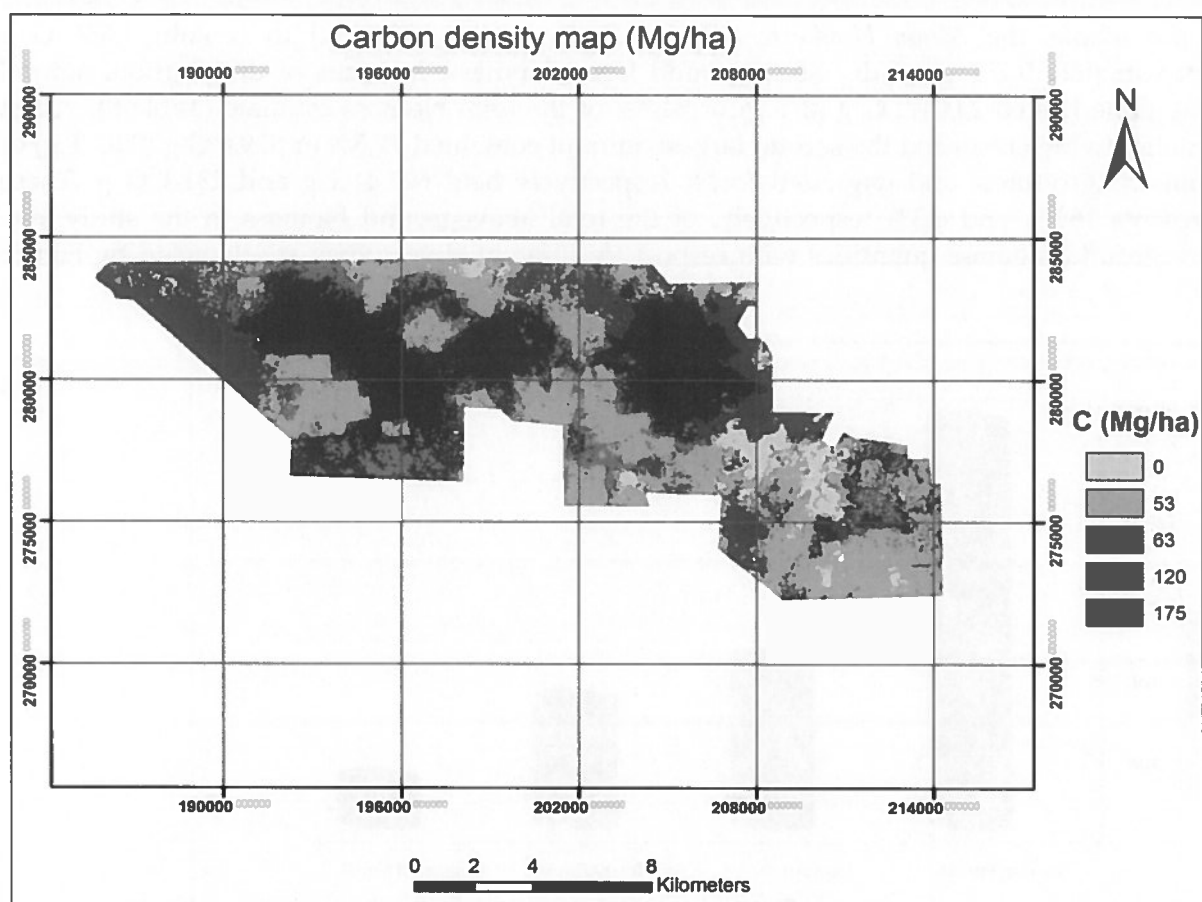


Figure 13: Carbon density map of the study area

Since carbon is a direct derivative from biomass, carbon stocks of the cover types followed the pattern of aboveground biomass levels. Invariably, natural forest was the most carbon-rich cover with density of  $174.8 \pm 36 \text{ Mg} \cdot \text{ha}^{-1}$ .

Table 10: Mean Carbon densities and total sequestered carbon in the cover types

Cover type	Area (ha)	Average aboveground Carbon stock ( $\text{Mg} \cdot \text{ha}^{-1}$ )			Total sequestered C (G g)	Percentage of sequestered C (%)
		Live trees	Herbaceous plants & litter	Total AGB Carbon		
Natural forest	5,724	171.2	3.6	$174.8 \pm 36$	1,000.6	54.3
Plantation	3,446	117.9	2.5	$120.4 \pm 42$	414.8	22.5
Agro-forest/Farm	5,794	52.4	1.5	$53.9 \pm 14$	312.	16.9
Degraded forest	1,808	59.7	4.2	$63.9 \pm 13$	115.5	6.3
Bare ground	854	-	-	-	-	-
Total area	17,626				1,843.1	100

AGB = aboveground biomass

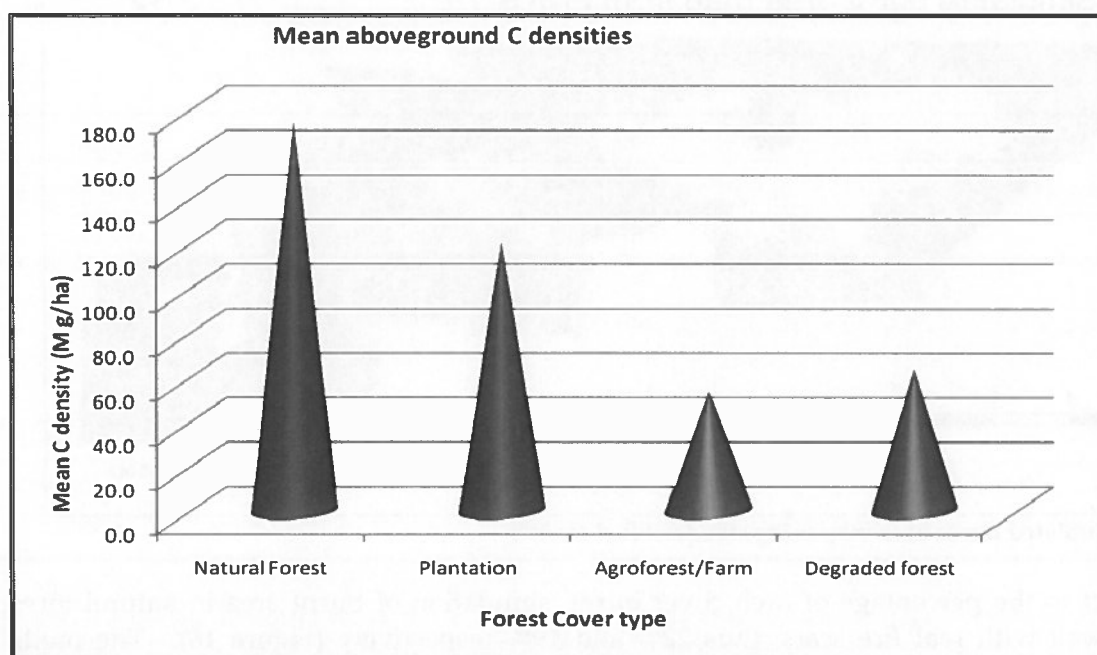


Figure 14: Mean aboveground carbon densities in different cover types

Canopy cover percentage and other vegetation characteristics of the different cover type are presented in Table 11.

Table 11: Vegetation characteristics of the cover types

Cover type	Canopy cover Percentage (%)	Shrub cover (%)	Herb (+litter) cover (%)
Natural Forest	65	50	60
Plantation	70	22	65
Agro-forestry	28	35	40
Degraded forest	31	60	75
Bare ground	-	-	-

### 3.3. FARSITE's simulation of fire behaviour

#### 3.3.1. Simulation using standard fuel models

Map indicating results of FARSITE's simulation of burnt area for the March 2007 fire is shown in Figure 15. This output was based on the standard fuel models (Anderson, 1982). Burnt areas resulting from real fires and that due to simulation are computed in Table 12. Real scars covered 7,754 ha or 44% of the total study area. A lower figure of 5,018 ha (28%) resulted from simulation.

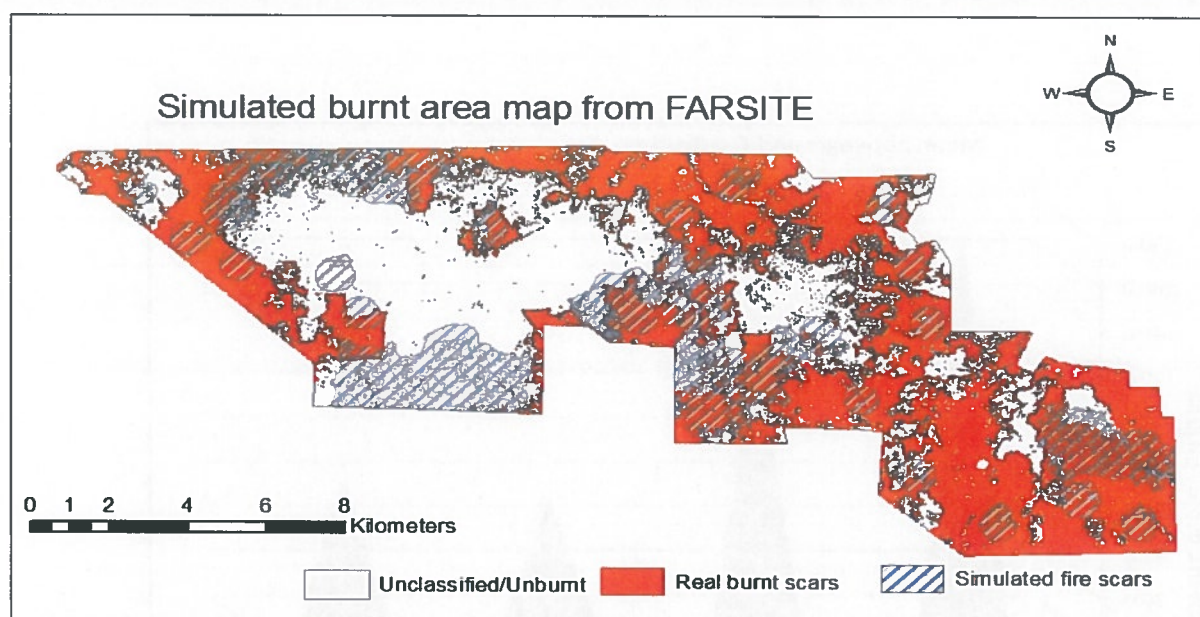


Figure 15: Simulated burnt area map using standard fuel models

With respect to the percentage of each cover burnt, simulation of burnt area in natural forest compared well with real fire scars; thus 22% and 19% respectively (Figure 16). The model under-estimated area burnt for plantations, agro-forest and bare ground. However, simulation results of burnt area in degraded forest (1,124 ha) was nearly twice larger than that identified from real fires [(589 ha) (Table 12)].

Table 12: Results of burnt area by real fires and FARSITE simulation using standard fuel models

Fuel model	Cover type	Total area (ha)	Area burnt (ha)		Percentage cover burnt (%)	
			Real scar	Simulation	Real	Simulation
10	Natural forest	5,724	1,099	1,285	19	22
9	Plantation	3,446	2,027	824	59	24
5	Agro-forest	5,794	3,717	1,784	64	31
4	Degraded forest	1,808	589	1,124	33	62
99	Bare ground	854	321	2	38	0
Total area		17,626	7,754	5,018	44	28



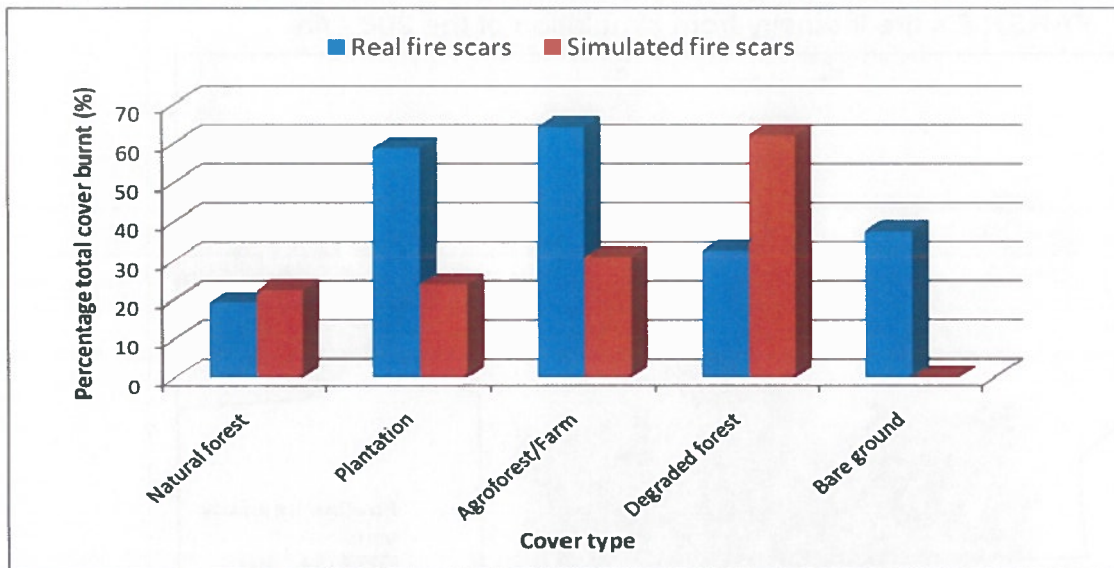


Figure 16: Proportion of real fire and standard fuel model fire scars in different cover types

### 3.3.2. Fire behaviour simulation using custom fuel models

Simulation of fire spread incorporating the two custom fuel models is shown in (Figure 17).

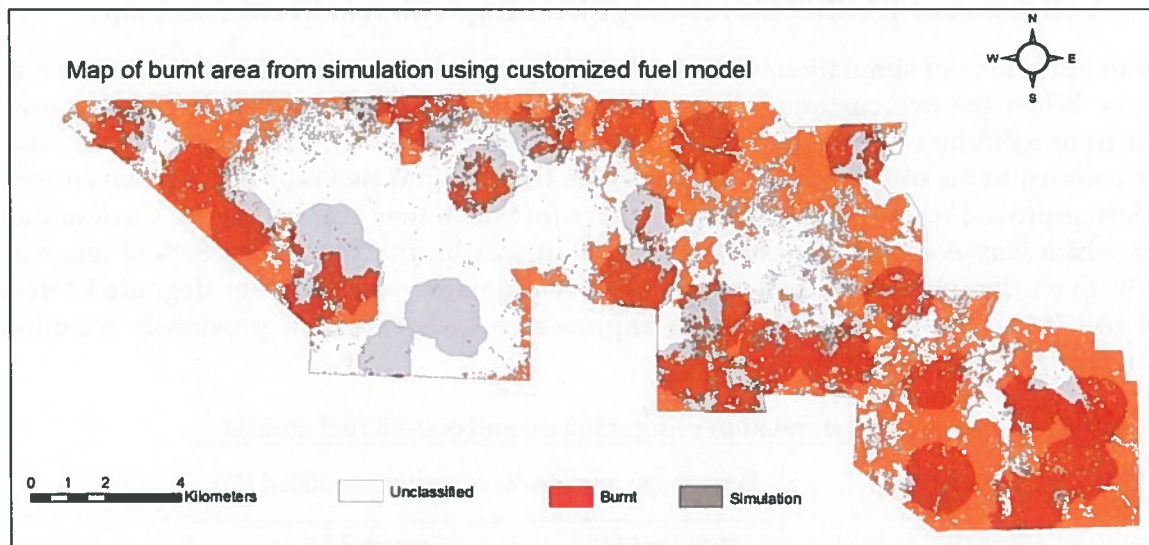


Figure 17 : Simulated burnt area map using custom fuel model

In the standard fuel models, fireline intensity ranged 0 – 2103 kW/m, with an average of 95 kW/m. When the custom fuel models were used fireline intensity ranged 0–2,911 kW/m averaging 148 kW/m. Higher intensity fires were generally found in degraded forest. Intensities were generally low in natural forest and plantation cover types (Figure 18). Fire rate of spread (ROS) averaged 0.5 m/min and 0.4 m/min respectively for custom and standard models. When the model was run with the percentile weather conditions, fireline intensity averaged 132, 155 and 144 kW/m for the 75<sup>th</sup>, 85<sup>th</sup> and 95<sup>th</sup> percentiles, respectively.

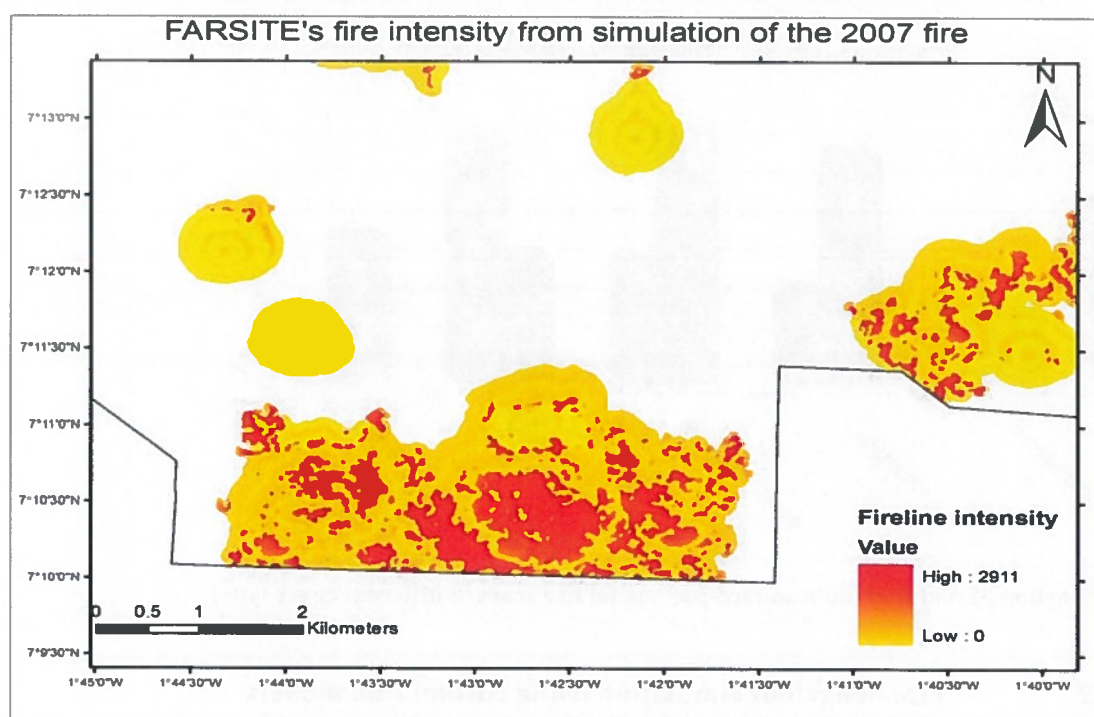


Figure 18: Section of fireline intensity from FARSITE simulation of the 2007 fire

### 3.4. Validation of FARSITE's results of burning with real burnt scar map

The overall burnt area of simulation with standard fuel models corresponded to 65% of the real burnt scars. When the two custom fuel models were input into the model overall burnt area increased from 5,018 ha to 6,333 ha. This figure corresponds to 82% of the total real scar area. This is in contrast to the 65% accuracy obtained with the standard fuel models. The two custom fuel models improved results of the two cover types for which they were assigned. Custom fuel model 15 which was assigned agro-forest increased in area burnt from 48% to 88% of real scar (Table 13). Even though custom fuel model 14 over-estimated area burnt in degraded forest (118% of real fire); the performance was an improvement over the 191% previously recorded using standard fuel models (Table 13)

Table 13: Results of burnt area of simulation using standard and custom fuel models

Fuel model code	Cover type	Percentage of real scar correctly simulated (%)	
		Standard FM	Custom FM
10	Natural forest	117	67
9	Plantation	41	80
*15	Agroforest/Farm	48	88
*14	Degraded forest	191	118
99	Bare ground	1	1

\*Custom fuel model, FM – fuel model

Proportions of area burnt in each cover type from both fuel models are compared with actual burnt area map are indicated in Figure 19.

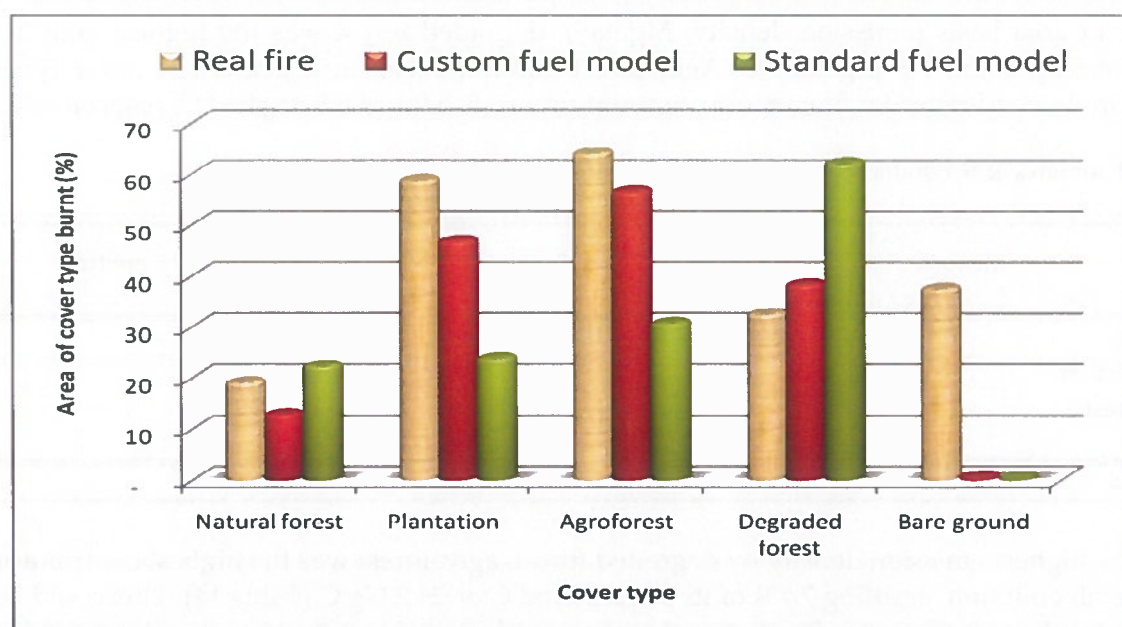


Figure 19: Comparison of cover type burnt using standard and custom fuel models

### 3.5. Modelling of fire-induced carbon emission

Spatial distribution of fire-induced carbon released during the 2007 fire in Afram Headwaters FR is shown in Figure 20.

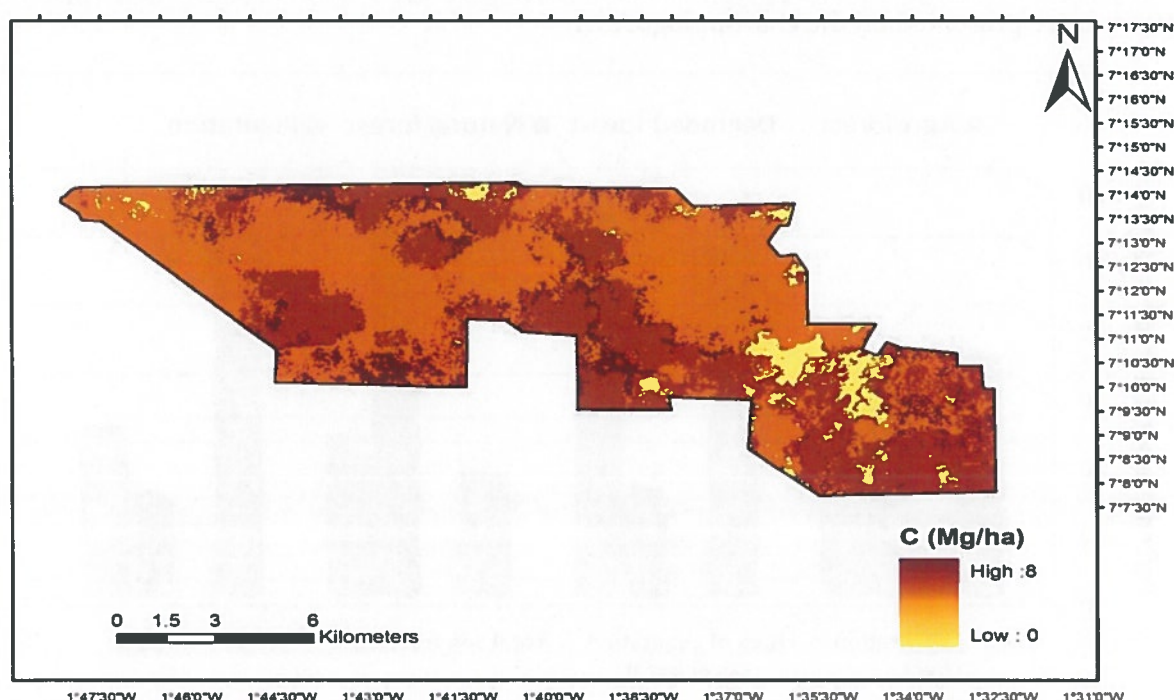


Figure 20: Map of fire-induced carbon emission

A summary of the estimated fire-induced carbon emissions is contained in Table 14. An estimated 46.2 Gg C was lost during the fires. This constituted about 2.5% of the total aboveground sequestered carbon estimated for the area. An average carbon release level of 6.4 Mg.ha<sup>-1</sup> C was estimated for the overall burnt area.

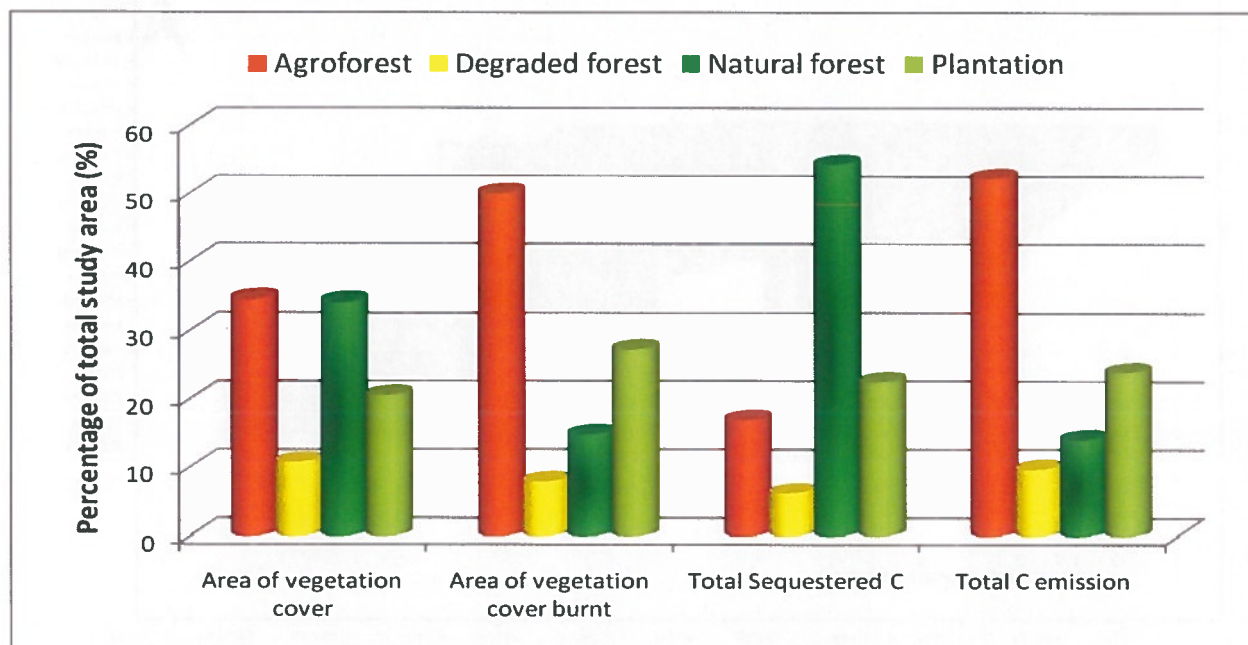


On per unit area basis (emission density,  $\text{Mg}\cdot\text{ha}^{-1}$ ), degraded forest was the highest emitting cover, releasing some  $7.6 \text{ Mg ha}^{-1} \text{ C}$ . Agro-forest, natural forest and plantation cover types followed in descending order of emission, amounting to 6.5, 5.9 and  $5.5 \text{ Mg}\cdot\text{ha}^{-1} \text{ C}$ , respectively.

**Table 14: Estimates of fire-induced carbon during the 2007 forest fire**

Cover type	Mean fire-induced C emitted ( $\text{Mg}/\text{ha}$ )	Total C emission (Gg)	Portion of sequestered C emitted (%)
Agroforest	6.5	24.2	7.7
Degraded forest	7.6	4.5	3.9
Natural forest	5.9	6.5	0.6
Plantation	5.5	11.1	2.7
Grand Total		46.2	2.5

Despite the highest emission density by degraded forest, agro-forest was the highest contributor to the overall emission, emitting 7.7% of its sequestered C or 24.2 Gg C (Table 14). This could be explained by the fact that agro-forest was the cover with the largest burnt area. About 64% of the cover got burnt during the 2007 wildfire in the study area. Plantation forest emitted 2.7% of its total sequestered C, making it the second largest emitter with 11.1 Gg C emissions. Even though natural forest emitted just 0.6% of its total sequestered C, it represented the third most important emitting cover. A total of 6.5 Gg C was released from this cover. Degraded forest with 4.5 Gg C, contributed the least to the overall C emission. In all this cover lost 3.9% of its total sequestered C. The overall pattern of area burnt, aboveground C stock of cover types and C emission are presented on the chart in Figure 21.



**Figure 21: Pattern of cover burnt and C emission in different cover types**

Thus total biomass consumed was 92.4 Gg. Using the emission factor of  $1615\text{g}/\text{kg}$  for tropical forests recommended by Yokelson *et al.* (2007), the resulting  $\text{CO}_2$  emitted amounted to 149.2 Gg  $\text{CO}_2$ .

## 4. Discussion

### 4.1. Dominant vegetation cover types and their aboveground biomass

#### 4.1.1. Classification of dominant vegetation cover types

The cover type classification identified agro-forest as the dominant vegetation type in *Afram Headwaters* Forest Reserve (FR). Natural forest cover occupied about a third of the entire FR. This result was not expected considering that the area was originally natural forest ecosystem, gazetted and legally protected from other land use. The results indicate that the FR is gradually losing its naturalness as a forest ecosystem. Though a surprising result, the trend of degradation is reasonable. The area, over the years, has experienced various levels of degradation as a result of timber over-exploitation, illegal logging, recurrent wildfires and encroachment for farming (Appiah *et al.*, ; Blay *et al.*, 2008). This has led to gradual decline in the natural cover of the area. This is in consonance with the dwindling of the forest estates in Ghana (Ministry of Lands and Forestry, 1996). Countrywide the rate of forest lost is estimated to be as high as 1.7% (FAO, 2000). Moreover Ghana's forest area steeply declined from about 8 million ha to about 1.7 million ha within the past century (Dykstra *et al.*, 1996; Friends of the Earth International, 1999). It has been reported that Ghana lost about 78% of its forest cover between the 1900's and 1989 (Hawthorne, 1989).

Government's policy to salvage declining forest resources lead to the introduction of forest plantations in degraded forests, using the *Modified Taungya System*. The concept which involves engagement of local communities in rehabilitation entitles them to benefit at the end of the rotation. This has made the practice very popular in the forest fringe communities. Therefore, the large area of agro-forest identified in the study area is reasonable. Forest plantations were first introduced to the Reserve in the 1970s, during which a lot of areas were planted with *Teak* (*Tectona grandis*). This explains the relative preponderance of *Teak* plantations in the study area.

Degraded forests did not amount to higher area as the other vegetation types. Nevertheless, the amount gives worrying hints about the structural and functional decline of the forest ecosystem. Indeed these are areas well dominated by the foreign invasive tree and shrub species, *Broussonetia papyrifera* and *Chromolaena odorata*, respectively. These are fast creeping in the remaining forest area. Anecdotal evidence suggests that degradation keep increasing in the area. This is in spite of the restoration operations by which large areas of the degraded forests are committed to agro-forests/ plantations annually since 2001.

#### 4.1.2. Classification accuracy assessment

An overall classification accuracy of 78.1% and a Kappa statistics of 0.72 were obtained from the vegetation cover classification. These statistics indicate that the assignment of image pixels to their corresponding cover types were reasonably accurate. However, the figure falls below the recommended target of 85% (Campbell, 2002; Foody, 2002). This is largely due the highly fragmented nature of the landscape due to the haphazard manner of intrusions in the ecosystem by fire and human activities. Furthermore, each vegetation type is composed of a mixture of several species, with some species occurring in almost all cover types. Even in monoculture plantations it was difficult picking homogenous spectral signatures due to the effect of fire and other management practices. The cover types therefore exhibited very similar spectral characteristics, making it difficult to put them in separate spectral classes. Therefore,

the classification accuracy achieved in this study, with an ASTER image of resolution not too high as Quickbird or IKONOS, was acceptable.

#### 4.1.3. Aboveground biomass in cover types

Detailed quantification of biomass in tropical forest ecosystems is of crucial importance in view the tremendous role of tropical forests in global climate regulation. Despite this recognition information on tropical forest biomass stocks are largely lacking (Sierra *et al.*, 2007). Inventory on aboveground biomass in this study was defined to encompass all aboveground biomass in living woody trees  $\geq 5\text{cm}$  DBH, and herbaceous plants (plants and litter). Aboveground biomass differed among cover types. The overall mean of  $206.5 \pm 52 \text{ Mg.ha}^{-1}$  is quite moderate among figures reported in literature for tropical forests. It is worth noting that generally the study area has a low level of tree stocking. This is reasonably so, considering the impacts of wildfire and human-inflicted disturbance in study area. The level of tree stocking has reduced drastically compared to the original vegetation. Indeed larger trees which contribute substantially to biomass stocks are very few. The natural forest vegetation has considerably reduced with it attendant loss in biomass. Nevertheless, these figures account for aboveground biomass in only the pools already defined above. Inclusion of the other pools could raise the average somehow. Cummings *et al.* (2002) during their studies in the Amazon found that coarse wood debris, standing dead plants, forest floor collectively contribute 12% ( $38 \text{ Mg.ha}^{-1}$ ) to the total aboveground biomass.

Notwithstanding these observations, the range  $107.8 - 349.6 \text{ Mg.ha}^{-1}$  recorded in this study is comparable to figures reported for live aboveground biomass by Gerwing (2002). Biomass density  $349.6 \text{ Mg.ha}^{-1}$  with respect to the natural forest cover alone compared well with results in several in other studies. This figure come close to an average density of  $400 \text{ Mg.ha}^{-1}$  reported by Nascimento & Laurance (2002) in the central Amazon. Cummings *et al.* (2002) found an average of  $280 \text{ Mg.ha}^{-1}$  for aboveground live tree biomass for an Amazonian open forest.

#### 4.2. Aboveground carbon densities of cover types and the total sequestered carbon of study area

Overall aboveground C density was low, a consequence of the low levels of biomass. Thus a reflection of the general level of aboveground biomass levels in the area. The most carbon-rich cover, natural forest, recorded C density of  $174.8 \pm 36 \text{ Mg.ha}^{-1}$ . Again this estimate is comparable with  $200 \text{ Mg.ha}^{-1}$  by Nascimento & Laurance, (2002) in the Amazon. The figure is even better relative to the average  $151 \pm 39 \text{ Mg.ha}^{-1}$  for the Amazon estimated by Fearnside *et al.* (1993) and Higuchi *et al.* (1994). It needs to be pointed out, however, that the estimates in this study are without the dead components of above ground C pools. Tutu (2008) who worked in Ghana obtained  $235 \text{ Mg.ha}^{-1}$  aboveground biomass C for the closed forest cover in the Bobiri Forest Reserve. However, there are some fundamental structural differences between these two sites. Bobiri Forest Reserve largely remains undisturbed and still maintains most of its original forest vegetation. Moreover, differences in allometric equations used in these two studies may have contributed to some of the differences.

#### 4.3. Modelling of fire behaviour/fireline intensity for the 2007 wildfire in the study area using FARSITE fire behaviour model.

Despite the wide range of fireline intensity values, intensity was generally low in all. This is indicated by the mean intensity values. The peak intensity values were few pixels mostly located on high elevations in degraded forest. This finding is consistent with the observation that disturbed forest areas tend to experience severe fires with high intensities due to higher fuel loads and reduced relative humidity (Cochrane, 2003). The same author reported of high severity of fire in disturbed tropical forests with fireline intensities of 82–728 kWm<sup>-1</sup> in disturbed forests. Indeed, the degraded forest cover was relatively drier than plantation and natural forest in view of the low canopy cover. Furthermore, there were huge fine fuels provided by the highly combustible shrub *Chromolaena odorata*. Thus the combined effect of drier environment, relatively higher wind speed facilitated by the open canopy and topography resulted in higher intensity in degraded forest. The interplay of these factors is quite complex. It is therefore difficult, in this case, to single out the most influential contributor to intensity. Understandably, fire intensity was low in the more closed canopy and humid cover types, thus natural forest and plantation.

Fireline intensities were not markedly different at the three weather scenarios. This is not surprising, because of the nearness of the weather variables at the percentiles. Nevertheless, the weather input were based on 10 years records, perhaps a longer term weather data would reveal different pattern.

#### 4.4. Model validation with real fire scar map

The total burnt area from FARSITE's simulation of the March 2007 fire amounted to 65% of the actual fire scar size. Simulation results were particularly good in the natural forest. However, FARSITE grossly under-estimated the area burnt for plantations and agro-forest cover types. Simulated burnt area in these cover types were less than half the real fire size. The fire rate of spread was unexpectedly low in the plantations, leading to low burnt area. This could be attributed to the high canopy cover in the plantations. Stratton (2006) found that under dense canopy cover the rate of fire spread is reduced because of the sheltering effect of the tree canopy. The same cannot be said for agro-forest however. This cover had the lowest canopy cover, thus the low area burnt cannot be explained by wind effects. The problem may have arisen because the fuel model could not have well represented this cover type. In direct contrast, however, burnt area was over-estimated by nearly double in the degraded forest. The situations in these two cover types therefore necessitated the need for custom fuel models that could improve burnt area simulation in the area.

Nevertheless, as noted by many authors, fuel mapping is difficult and expensive (Arroyo *et al.*, 2008; Keane *et al.*, 2000). Yet fuel maps/models remain a critical input in fire behaviour models. The two custom models developed in this study gave a better representation of fire spread than their corresponding standard fuel models. The overall burnt area, as a percentage of real fire scars, increased from 65% to 82%. Arca *et al.* (2006) found good accuracy in fire behaviour when they ran FARSITE with custom models.

Fuels are expected to be unavailable for non-vegetated/bared areas. Therefore the one percent burnt recorded by both standard and custom fuel simulations should be tolerable. Surprisingly, real scar map over-estimated burnt area on non-vegetated sites. This result, though unexpected, could have resulted due to some misunderstanding in the land cover classification. In this study, the land cover classified as bare was considered to include settlement/villages, denuded



and exposed soil surfaces as well as other non-vegetation related land uses. These were observed during the field work in November 2008. It is possible that some of these areas may have experienced fire at the time of mapping in 2007. Furthermore, land use pattern in the area is largely unstable. Therefore the class of a cover may have changed in the period between the two maps. This is more likely in view of the fact that some severely burnt areas may not have regained their vegetation class.

Perhaps, better results could be obtained if weather data specific to the study location was available. The weather data used in the model was the regional data collected at Kumasi, some 40km away from the study area. Therefore fine details of weather records representing local conditions pertaining to the site were not well captured by the data used.

#### 4.5. Modelling of fire-induced carbon emission from forest cover types under known fire weather conditions during the 2007 fires in the study area

The uncertainty in quantifying fire-induced C emission are as a result of spatial variations in pre-fire C stocks as well as variations in the quantity of C consumed during fire (French *et al.*, 2004). In this study the spatial variation in biomass was addressed by the different biomass stocks of the cover types. Difference in biomass consumed was related to the level of intensity of the fire. Even though data for comparison in similar environment is rare, the estimates appear interesting. Cochrane (2003) reported that there exist considerable variations in carbon emissions from tropical wildfires. The range 5.5 – 7.6 Mg.ha<sup>-1</sup> C obtained in this work is reasonably within that reported by Cochrane (2003). Notwithstanding this observation, the values obtained fall far below experimental values recorded in the tropics by Yokelson *et al* (2007).

Interestingly, the C emissions model indicates that cover types with the least C density (degraded forest and agro-forest) released the most C per hectare. Again the denser C areas emitted the least C per hectare. This trend in emission was not predicted. More C-rich cover types were expected to release more C, and vice versa. However, the trend is consistent with the underlying forest conditions and their influence on fire behaviour. Natural forest and plantation had more canopy cover, making them more humid than the very open agro-forest and degraded forest. Thus the open forest canopy in the less C-rich agro-forest and degraded forest cover types permitted more solar radiation to dry the otherwise humid forest floor. In the process more fine fuels are generated for burning (Gerwing, 2002). Moreover, forests with reduced canopies are more vulnerable to fire because their capability to sustain moisture is also reduced (Cochrane, 2003). Indeed simulation results indicated that fire was most intense in the degraded forest. Evidence from the field indicate that the degraded forest, and to some extent agro-forest, experience frequent burnings. Degraded forest areas in particular are dominated by the most invasive tree and shrub species, *Broussonetia papyrifera* and *Chromolaena odorata* respectively (Figure 22). These two species provide considerable amount of combustible matter leading to more biomass loss during burning. The spread of these species is facilitated by extensive deforestation and bushfires (Bosu & Apetorgbor, 2007).





Figure 22: Portion of degraded forest showing an open canopy & the invasive species *Chromolaena odorata*

Notwithstanding these findings, some assumptions used in this study are worth noting. Due to limited data regarding fuel models parameterization, and the amount of biomass available as fuel, various assumptions had to be made in this study. Despite these limitations, however, the study constitutes a significant step towards achieving a more improved estimation of fire-induced emissions in Ghana's tropical forest environments. Amiro *et al.* (2001) developed a method to estimate carbon emission for Canada's wildfires based on limited data and myriad assumptions on weather, fuel and fire behaviour. Further refinements lead to the development of a more accurate system for direct estimation of Canadian national emissions from fire (de Groot *et al.*, 2007). More significantly, this study has demonstrated that fire-induced emissions in countries with less developed fire and emission monitoring systems can be estimated when Remote Sensing & GIS techniques are coupled with off-the-shelf fire behaviour models. Due to the non-existence of emissions data and the limited time for this study the model output of emission estimates could not be validated. Major recommendations for further studies are validation of emission estimates realised and the development of fuel models for tropical forest conditions. Perhaps, model output would be significantly affected if more representative weather data at finer scale was available for the study location.

## 5. Conclusions

### 5.1. What are the forest cover types in the study area and their aboveground biomass stocks?

- Four forest cover types along with bare ground were identified and mapped. These were natural forest, plantation, agro-forest and degraded forest.
- Aboveground biomass stocks of the cover types were: natural forest 349.6 Mg.ha<sup>-1</sup>; plantation 240.8 Mg.ha<sup>-1</sup>; degraded forest 127.8 Mg.ha<sup>-1</sup> and agro-forest 107.8 Mg.ha<sup>-1</sup>.
- Total aboveground biomass amounted to 3,686 Gg dry matter.

### 5.2. What are the aboveground carbon densities of the forest cover types; and the total sequestered carbon of the study area?

- Natural forest recorded the highest C density of 174.8 ± 36 Mg.ha<sup>-1</sup>, followed by plantation with 120.4 ± 42 Mg.ha<sup>-1</sup>, degraded forest 63.9 ± 13 Mg.ha<sup>-1</sup> and agro-forest 53.9 ± 14 Mg.ha<sup>-1</sup> C.
- Sequestered C in living aboveground biomass totalled 1,843.1 Gg C.

### 5.3. Which areas experienced the most intense fire under weather conditions during the March 2007 fire?

- Degraded forest experienced the most intensity fires. Least intensities were found in natural forest and plantation cover types.

### 5.4. How accurate is FARSITE's simulation of burnt area?

- With standard fuel models burnt area size was 65% of real burnt scar. Simulation generally under-estimated burnt area for the entire study area.
- Custom fuel models improved estimation of burnt area from 65% to 82% of real fire scars, and gave good representation for cover types whose burnt areas had previously been over-estimated or under-estimated by standard fuel models.

### 5.5. What are the estimates of fire-induced carbon emitted from forest cover types and the overall emission during the March 2007 fire in the study area?

- Emission densities/rates were 5.5 Mg.ha<sup>-1</sup> C; 5.9 Mg.ha<sup>-1</sup> C; 6.5 Mg.ha<sup>-1</sup> and 7.6 Mg.ha<sup>-1</sup> C for plantation, natural forest, agro-forest and degraded forest, respectively.
- Overall, 46.2 Gg C was released during the 2007 fire. This is equivalent to 149.2 Gg of CO<sub>2</sub> emission.

### 5.6. Which forest cover types emitted the most fire-induced carbon from the 2007 fires?

- Agro-forest emitted the largest amount of C, totalling 24.2 Gg (52.3% of total emission); followed by plantation 11.1 Gg C (24% of total emission). Third largest emitter was

natural forest with 6.5 Gg (14% of the overall C emission). Degraded forest was the least with 4.5Gg C or 9.7% of the overall total emission.

## 6. Recommendations

### 6.1. Estimation of biomass/carbon stocks

- There is currently no local biomass equation for Ghana. There may be limitations in the biomass/carbon estimates due to the allometric equation adopted. Development of allometric equations underpinned by the local Ghanaian conditions is strongly recommended.
- Representation of the spatial variability in carbon distribution as well as other forest attributes in this study would be enhanced if geo-statistical analysis and spectral vegetation indices were used. Future studies should incorporate these aspects.
- Below ground and dead woody biomass components are likely to influence fire-induced carbon emissions. Yet they were not included in this study. Future research should consider incorporating biomass in these pools.

### 6.2. Fire behaviour fuel models for tropical forest conditions

- The absence of fuel models specific to fuel characteristics of the study area remained a key constraint in this study. There is currently no fire behaviour fuel models specifically constructed to suit tropical forest ecosystems. In view of the increasing havoc of tropical wildfires in recent decades, and its consequence on global emissions, research attention is urgently required in this area of tropical forest science.

### 6.3. Fire-induced carbon emissions modelling

- Further research should consider using energy release approach for emissions assessment. This would involve investigating the suitability of consumption models including FCCS, CONSUME, FOFEM and FEPS for the study area. It will be worthwhile to compare the results from such approaches with that obtained in this study.
- Development of possible mathematical/statistical relationship linking spectral indices from burnt surfaces to fuel consumption and fire intensity would greatly reduce data inputs in such studies. Such an achievement could further provide simplified methods for estimating fire-induced carbon. There is definitely the need for more research on the relationship between fire intensity and fuel consumption.
- This study did not consider emission of trace gases species. Future work should consider determination of emission factors and emission of other trace gases; as well as their effects on human health and the ecological balance at the country level. Detailed comparison of emission from biomass burning to other sectors such as industry and transportation would be of great interest.
- In view of the non existence of fire-induced emissions data and the limited time for this study validation of emission estimates was not done. Further work in this direction is strongly recommended.
- Weather data collected at the local level at finer temporal resolution would improve model results. Data used in the model was obtained from weather station some 40km away from the study area. Future research may consider getting weather data from satellite systems.

## 7. References

- Alamgir, M., & Al-Amin, M. (2008). Allometric models to estimate biomass organic carbon stock in forest vegetation (Abstract). *Journal of Forestry Research* 19(2), 101-106.
- Amiro, B. D., Todd, J. B., Wotton, B. M., Logan, K. A., Flannigan, M. D., Stocks, B. J., Mason, J. A., Martell, D. L., & Hirsch, K. G. (2001). Direct carbon emissions from Canadian forest fires, 1959-1999. *Canadian Journal of Forest Research*, 31 512-525.
- Anaya, J. A., Chuvieco, E., & Palacios-Orueta, A. Aboveground biomass assessment in Colombia: A remote sensing approach. *Forest Ecology and Management, In Press, Corrected Proof*.
- Anderson, E. (1982). Aids to Determining Fuel Models For Estimating Fire Behavior. *USDA, Forest Service, Intermountain Forest and Range Experiment Station Ogden, UT 84401 General Technical Report INT-122*.
- Appiah, M., Blay, D., Damnyag, L., Dwomoh, F., Pappinen, A., & Luukkanen, O. Dependence on forest resources and tropical deforestation in Ghana. *Environment, Development and Sustainability, In Press*.
- Arca, B., Duce, P., Pellizzaro, G., Laconi, M., Salis, M., & Spano, D. (2006). Evaluation of FARSITE simulator in Mediterranean shrubland. *Forest Ecology and Management*, 234(Supplement 1), S110-S110.
- Arroyo, L. A., Pascual, C., & Manzanera, J. A. (2008). Fire models and methods to map fuel types: The role of remote sensing. *Forest Ecology and Management*, 256(6), 1239-1252.
- Berjak, S. G., & Hearne, J. W. (2002). An improved cellular automaton model for simulating fire in a spatially heterogeneous Savanna system. *Ecological Modelling*, 148(2), 133-151.
- Blay, D., Appiah, M., Damnyag, L., Dwomoh, F., Luukkanen, O., & Pappinen, A. (2008). Involving local farmers in rehabilitation of degraded tropical forests: some lessons from Ghana. *Environment, Development and Sustainability*, 10(4), 503-518.
- Borchert, M. I., & Odion, D. C. (1995). Fire Intensity and Vegetation Recovery in Chaparral: A Review. *Brushfires in California Wildlams: Ecology and Resource Management*.
- Bosu, P. P., & Apetorgbor, M. M. (2007). *Broussonetia papyrifera* in Ghana: Its Invasiveness, Impact and Control attempts. Retrieved August 19, 2008, from <http://www.fao.org/forestry/media/12727/1/0/>
- Brown, S. (1997). Estimating Biomass and Biomass Change of Tropical Forests: a Primer. *FAO Forestry Paper - 134*. FAO, Rome.
- Campbell, J. B. (2002). *Introduction to Remote Sensing*. Taylor and Francis, London 621pp.
- Carmel, Y., Paz, S., Jahashan, F., & Shoshany, M. (2009). Assessing fire risk using Monte Carlo simulations of fire spread. *Forest Ecology and Management*, 257(1), 370-377.
- Chambers, J. Q., Asner, G. P., Morton, D. C., Anderson, L. O., Saatchi, S. S., Espirito-Santo, F. D. B., Palace, M., & Souza Jr, C. (2007). Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends in Ecology & Evolution*, 22(8), 414-423.



- Christian, T. J., Kleiss, B., Yokelson, R. J., Holzinger, R., Crutzen, P. J., Hao, W. M., Saharjo, B. H., & Ward, D. E. (2003). Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels (Abstract). *J. Geophys. Res.*, 108.
- Cochrane, M. A. (2003). Fire science for rainforests. *Nature*, 421(6926), 913-919.
- Cramer, W., Bondeau, A., Schaphoff, S., Lucht, W., Smith, B., & Sitch, S. (2004). Tropical Forests and the Global Carbon Cycle: Impacts of Atmospheric Carbon Dioxide, Climate Change and Rate of Deforestation. *Philosophical Transactions: Biological Sciences*, 359(1443), 331-343.
- Cummings, D. L., Boone Kauffman, J., Perry, D. A., & Flint Hughes, R. (2002). Aboveground biomass and structure of rainforests in the southwestern Brazilian Amazon. *Forest Ecology and Management*, 163(1-3), 293-307.
- Dasgupta, S., Qu, J. J., Hao, X., & Bhoi, S. (2007). Evaluating remotely sensed live fuel moisture estimations for fire behavior predictions in Georgia, USA. *Remote Sensing of Environment*, 108(2), 138-150.
- de Groot, W. J. (2006a). Modeling Canadian wildland fire carbon emissions with the Boreal Fire Effects (BOFIRE) model. In *Proceedings of the 5th International Conference on Forest Fire Research*. 27-30 November 2006, Figueira da Foz, Portugal. (Ed. Viegas, D. X.). Elsevier BV: Amsterdam.
- de Groot, W. J. (2006b). Modeling Canadian wildland fire carbon emissions with the Boreal Fire Effects (BORFIRE) model. *Forest Ecology and Management*, 234(Supplement 1), S224-S224.
- de Groot, W. J., Landry, R., Kurz, W. A., Anderson, K. R., Englefield, P., Fraser, R. H., Hall, R. J., Banfield, E., Raymond, D. A., Decker, V., Lynham, T. J., & Pritchard, J. M. (2007). Estimating direct carbon emissions from Canadian wildland fires. *International Journal of Wildland Fire*, 16 593-606.
- De Santis, A., & Chuvieco, E. (2007). Burn severity estimation from remotely sensed data: Performance of simulation versus empirical models. *Remote Sensing of Environment*, 108(4), 422-435.
- Dwyer, E., Pinnock, S., Gregoire, J. M., & Pereira, J. M. C. (2000). Global spatial and temporal distribution of vegetation fire as determined from satellite observations. *International Journal of Remote Sensing*, 21(6), 1289 - 1302.
- Dykstra, D. P., Kowero, G. S., Ofosu-Asiedu, A., & Kio, P. (eds.) (1996). Promoting stewardship of forests in the humid forest zone of Anglophone West and Central Africa, final report of a collaborative research project undertaken by UNEP and CIFOR. Center for International Forestry Research (CIFOR). Jakarta, Indonesia, 103 pp.
- Environmental Protection Agency (2000). Report on Ghana's national communication on climate change.
- Falkowski, M. J., Gessler, P. E., Morgan, P., Hudak, A. T., & Smith, A. M. S. (2005). Characterizing and mapping forest fire fuels using ASTER imagery and gradient modeling. *Forest Ecology and Management*, 217(2-3), 129-146.
- FAO. (2000 ). Global forest resources assessment main report. FAO Forestry Paper 140, 479 pp.
- FAO. (2007). State of the World's Forests 2007 (pp. 144). Rome: FAO.



- Fearnside, P. M., Leal, N. J., & Fernandes, F. M. (1993). Rainforest burning and the global carbon budget: Biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon. *J. Geophys. Res.*, 98 (9), 16,733-716,743.
- Finney, M. A. (2004). FARSITE: Fire Area Simulator – Model Development and Evaluation. Res. Pap. RMRS-RP-4, Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. . 47 p.
- Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, 80(1), 185-201.
- French, N. H. F., Goovaerts, P., & Kasischke, E. S. (2004). Uncertainty in estimating carbon emissions from boreal forest. *JOURNAL OF GEOPHYSICAL RESEARCH*, 109(D14S08), 1-12
- Friends of the Earth International (1999). Cut and run: illegal logging and timber trade in the tropics. International Development Research Centre, Ottawa.
- Gerwing, J. J. (2002). Degradation of forests through logging and fire in the eastern Brazilian Amazon. *Forest Ecology and Management*, 157(1-3), 131-141.
- Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *ENVIRONMENTAL RESEARCH LETTERS*, 2, 045023
- Hall, J. B., & Swaine, M. D. (1981). *Distribution and ecology of vascular plants in a tropical rain forest: Forest vegetation in Ghana*: W. Junk, The Hague.
- Hall, J. N. (1991). Comparison of fuel consumption between high intensity and moderate intensity fires in logging slash. *Northwest Science*, 65(4), 158-165.
- Hawthorne, W. D. (1989). The flora and vegetation of Ghana's forests. In: Ghana forest inventory proceedings (pp. 8-13). Overseas Development Agency/Ghana Forestry Department, Accra.
- Higuchi, N., Santos, J. M., Imanaga, M., & Yoshida, S. (1994). Aboveground biomass estimate for Amazonian tropical moist forests, . *Mem. Fac. of Agric.*, , 30(39), 43-54.
- IPCC. (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Retrieved August 13, 2008, from [http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf\\_contents.html](http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html)
- Jansen, J. R. (1996). *Introductory digital image processing*. New Jersey: Trentice Hall.
- Kasischke, E. S., & Bruhwiler, L. P. (2003). Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. *JOURNAL OF GEOPHYSICAL RESEARCH*, VOL. 108 (D1, 8146), 14.
- Kasischke, E. S., Hyer, E. J., Novelli, P. C., Bruhwiler, L. P., French, N. H. F., Sukhinin, A. I., Hewson, J. H., & Stocks, B. J. (2005). Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide. *Global Biogeochem. Cycles*, 19, GB1012.
- Keane, R. E., Mincemoye, r. A., Schmidt, K. M., Long, D. G., & Garner, J. L. (2000). Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico. *Gen. Tech. Rep. RMRS-GTR-46-CD*. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 126 p.

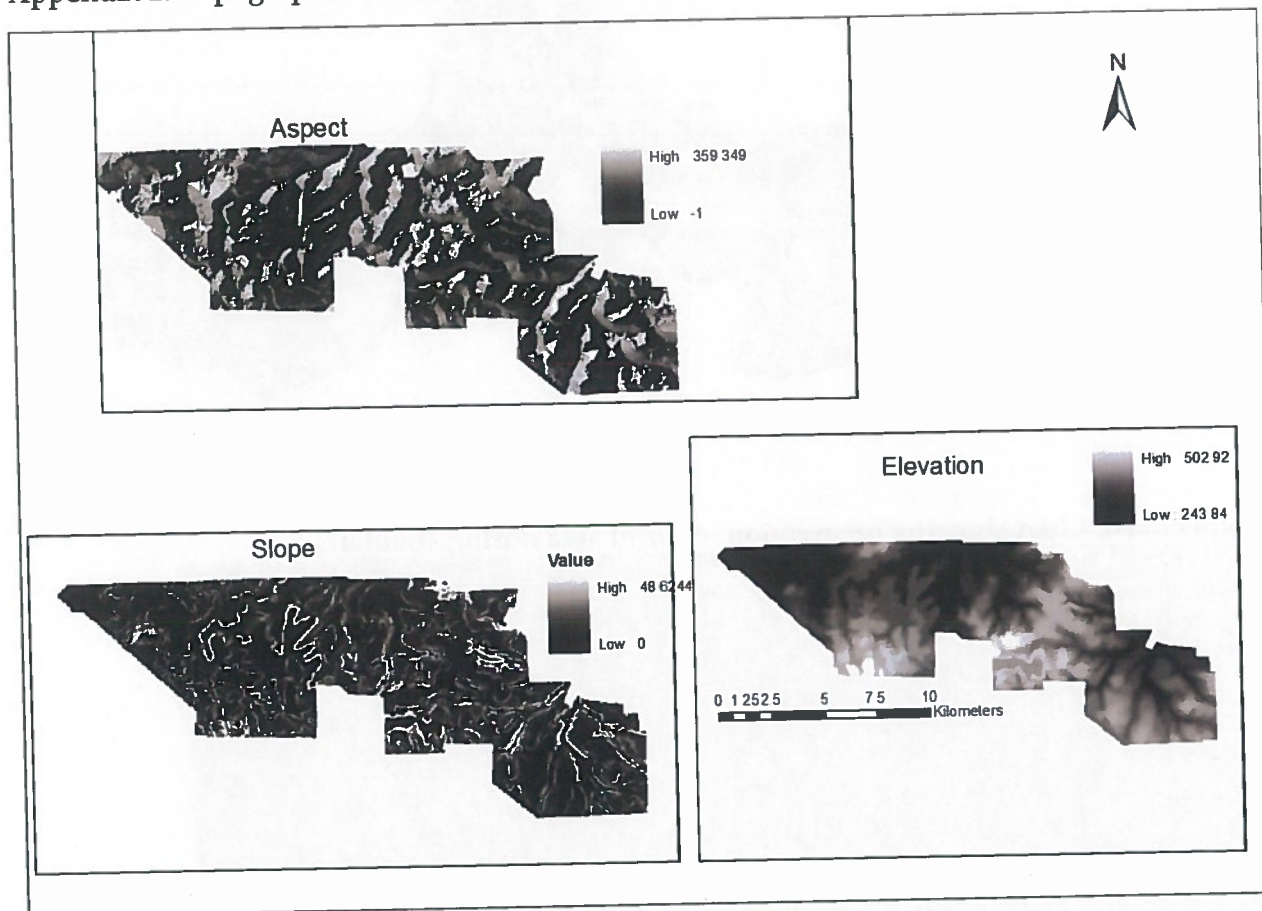
- Lavorel, S., Flannigan, M., Lambin, E., & Scholes, M. (2007). Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems. *Mitigation and Adaptation Strategies for Global Change*, 12(1), 33-53.
- Li, Z., Nadon, S., Cihlar, J., & Stocks, B. J. (2000). Satellite-based mapping of Canadian boreal forest fires: evaluation and comparison of algorithms. *International Journal of Remote Sensing*, 21(6), 3071-3082.
- Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2003). *Remote Sensing and Image Interpretation* (5th ed.): John Wiley & Sons Inc.
- Lu, A., Tian, H., Liu, M., Liu, J., & Melillo, J. M. (2006). Spatial and temporal patterns of carbon emissions from forest fires in China from 1950 to 2000. *JOURNAL OF GEOPHYSICAL RESEARCH*, 111(D05313).
- Mbow, C., Goïta, K., & Béné, G. B. (2004). Spectral indices and fire behavior simulation for fire risk assessment in savanna ecosystems. *Remote Sensing of Environment*, 91(1), 1-13.
- Ministry of Lands and Forestry (1996). Forestry development master plan (pp. 26). Accra, Ghana: MLF
- Mohammed, Y. (2008). *Modelling forest fire risk using remote sensing and GIS : a case study in the Afram headwaters forest reserve of the transitional forest zone of Ghana*. ITC, Enschede.
- Mollicone, D., Freibauer, A., Schulze, E. D., Braatz, S., Grassi, G., & Federici, S. (2007). Elements for the expected mechanisms on 'reduced emissions from deforestation and degradation, REDD' under UNFCCC. *ENVIRONMENTAL RESEARCH LETTERS* 2 (045024), 7.
- Mutlu, M., Popescu, S. C., & Zhao, K. (2008). Sensitivity analysis of fire behavior modeling with LIDAR-derived surface fuel maps. *Forest Ecology and Management*, 256(3), 289-294.
- Nascimento, H. E. M., & Laurance, W. F. (2002). Total aboveground biomass in central Amazonian rainforests: a landscape-scale study. *Forest Ecology and Management*, 168(1-3), 311-321.
- Offinso Municipal Assembly, (2006). District profile. from <http://www.ghanadistricts.com/districts/>
- Olander, L. P., Gibbs, H. K., Steininger, M., Swenson, J. J., & Murray, B. C. (2008). Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and method. *Environ. Res. Lett.* , 3 025011 11pp.
- Osei, E. M. J., & Zhou, Y. X. (2004). Land Cover Change detection in West Jilin using ETM+ images. *Journal of Geoscientific Research in N. E. Asia*, 7(1), 74-84.
- Ottmar, R. D., Vihnanek, R. E., Miranda, H. S., Sato, M. N., & Andrade, S. M. A. (2001). Stereo Photo Series for Quantifying Cerrado Fuels in Central Brazil - Volume I. *Gen. Tech. Rep. PNW-GTR-519*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 87 p.
- Palacios-Orueta, A., Chuvieco, E., Parra, A., Carmona-Moreno, C., eacute, & sar. (2005). Biomass Burning Emissions: A Review of Models Using Remote-Sensing Data. *Environmental Monitoring and Assessment*, 104, 189-209.

- Pearson, T., & Brown, S. (2004). Exploration of the Carbon Sequestration Potential of Classified Forests in the Republic of Guinea: Guidelines for measuring and monitoring carbon in forests and grasslands. Developed for the US Agency for International Development. Winrock International, Arlington, VA.
- Pearson, T., Walker, S., & Brown, S. (2005). Sourcebook for Land Use, Land-Use Change and Forestry Projects. Retrieved 21 January, 2009 from [http://www.winrock.org/ecosystems/files/Winrock-BioCarbon\\_Fund\\_Sourcebook-compressed.pdf](http://www.winrock.org/ecosystems/files/Winrock-BioCarbon_Fund_Sourcebook-compressed.pdf)
- Potter, C., Brooks Genovese, V., Klooster, S., Bobo, M., & Torregrosa, A. (2001). Biomass burning losses of carbon estimated from ecosystem modeling and satellite data analysis for the Brazilian Amazon region. *Atmospheric Environment*, 35(10), 1773-1781.
- Rothermel, R. C., & Deeming, J. E. (1980). MEASURING AND INTERPRETING FIRE BEHAVIOR FOR CORRELATION WITH FIRE EFFECTS. *USDA Forest Service General Technical Report INT-93*.
- Ryu, S.-R., Chen, J., Zheng, D., & Lacroix, J. J. (2007). Relating surface fire spread to landscape structure: An application of FARSITE in a managed forest landscape. *Landscape and Urban Planning*, 83(4), 275-283.
- Scott, J. H., & Burgan, R. E. (2005). Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.
- Seiler, W., & Crutzen, P. J. (1980). Estimates of gross and net fluxes of carbon between the biosphere and atmosphere *Clim. Change* 2 207-247.
- Sierra, C. A., del Valle, J. I., Orrego, S. A., Moreno, F. H., Harmon, M. E., Zapata, M., Colorado, G. J., Herrera, M. A., Lara, W., Restrepo, D. E., Berrouet, L. M., Loaiza, L. M., & Benjumea, J. F. (2007). Total carbon stocks in a tropical forest landscape of the Porce region, Colombia. *Forest Ecology and Management*, 243(2-3), 299-309.
- Skutsch, M., Bird, N., Trines, E., Dutschke, M., Frumhoff, P., de Jong, B. H. J., van Laake, P., Masera, O., & Murdiyarso, D. (2007). Clearing the way for reducing emissions from tropical deforestation. *Environmental Science & Policy*, 10(4), 322-334.
- Smirnova, E., Bergeron, Y., & Brais, S. (2008). Influence of fire intensity on structure and composition of jack pine stands in the boreal forest of Quebec: Live trees, understory vegetation and dead wood dynamics. *Forest Ecology and Management*, 255(7), 2916-2927.
- Smith, A. M. S., Wooster, M. J., Drake, N. A., Dipotso, F. M., Falkowski, M. J., & Hudak, A. T. (2005). Testing the potential of multi-spectral remote sensing for retrospectively estimating fire severity in African Savannas. *Remote Sensing of Environment*, 97(1), 92-115.
- Stephens, S. L. (1998). Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. *Forest Ecology and Management*, 105(1-3), 21-35.
- Stratton, R. D. (2004). Assessing the Effectiveness of Landscape Fuel Treatments on Fire Growth and Behavior. *Journal of Forestry*

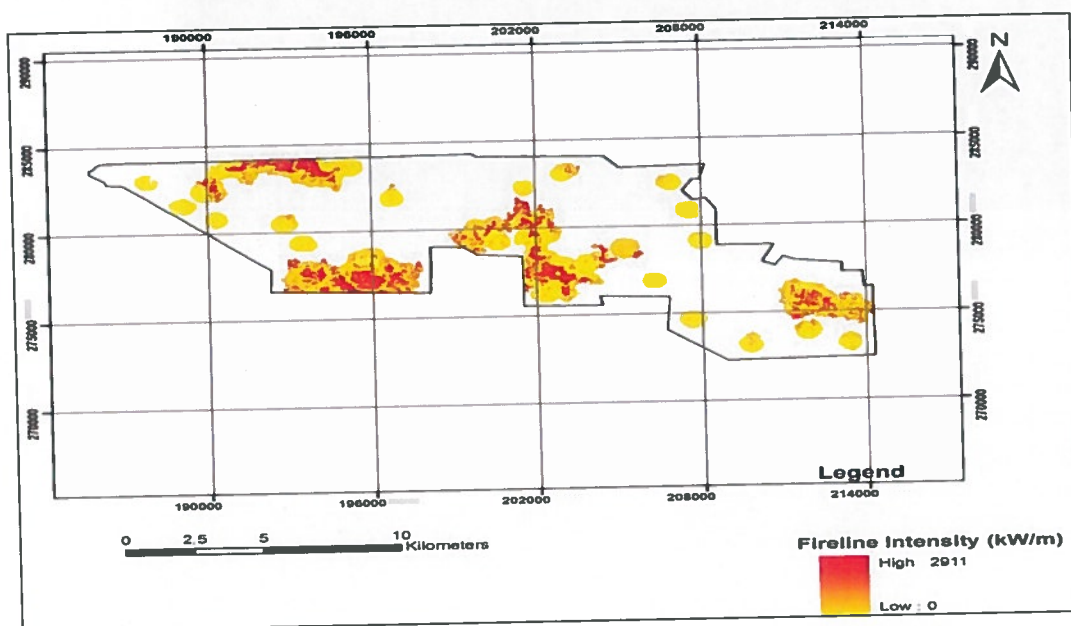
- Stratton, R. D. (2006). Guidance on spatial wildland fire analysis: models, tools, and techniques. General Technical Report RMRS-GTR-18, USDA Forest Service, Rocky Mountain Research Station
- Swaine, M. D., Agyeman, V. K., Kyereh, B., Orgle, T. K., Thompson, J. T., & Veenendaal, E. M. (1997). *Ecology of Forest Trees in Ghana*. Aberdeen, UK: University of Aberdeen.
- Tacconi, L., Moore, P., & Kaimowitz, D. (2007). Fires in tropical forests – what is really the problem? lessons from Indonesia. *Mitigation and Adaptation Strategies for Global Change*, 12(1), 55-66.
- Tan, Z., Tieszen, L., Zhu, Z., Liu, S., & Howard, S. (2007). An estimate of carbon emissions from 2004 wildfires across Alaskan Yukon River Basin. *Carbon Balance and Management*, 2(1), 8.
- Tutu, B. D. (2008). *Assessing the effects of land-use/cover change on ecosystem service in Ejisu-Juaben District, Ghana: The case study of carbon sequestration*. ITC, Enschede.
- UNEP. (2008). Global Environmental Outlook-2000. Retrieved 21 May 2008, from <http://www.unep.org/geo2000/english/0040.htm>
- Wang, C., & Qi, J. (2008). Biophysical estimation in tropical forests using JERS-1 SAR and VNIR imagery. II. Aboveground woody biomass. *International Journal of Remote Sensing*, 29, 6827-6849.
- Williams, C., Hanan, N., Neff, J., Scholes, R., Berry, J., Denning, A. S., & Baker, D. (2007). Africa and the global carbon cycle. *Carbon Balance and Management*, 2(1), 13.
- Yassemi, S., Dragicevic, S., & Schmidt, M. (2008). Design and implementation of an integrated GIS-based cellular automata model to characterize forest fire behaviour. *Ecological Modelling*, 210(1-2), 71-84.
- Yokelson, R. J., Karl, T., Artaxo, P., Blake, D. R., Christian, T. J., Griffith, D. W. T., Guenther, A., & Hao, W. M. (2007). The Tropical Forest and Fire Emissions Experiment: overview and airborne fire emission factor measurements. *Atmospheric Chemistry and Physics*, 7(19), 5175-5196.

## 8. Appendix

### Appendix 1: Topographic variables used in the model

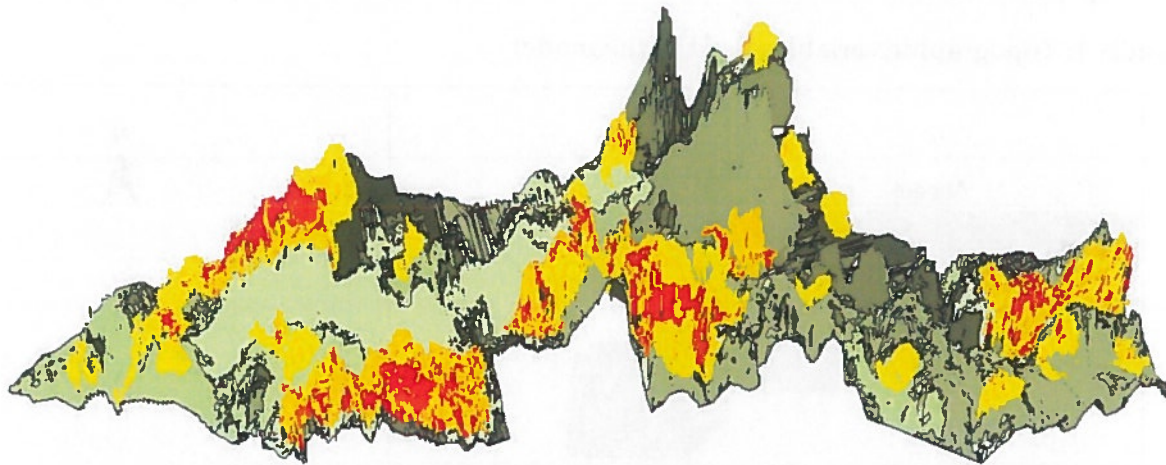


### Appendix 2: Spatial distribution of fireline intensity from simulation

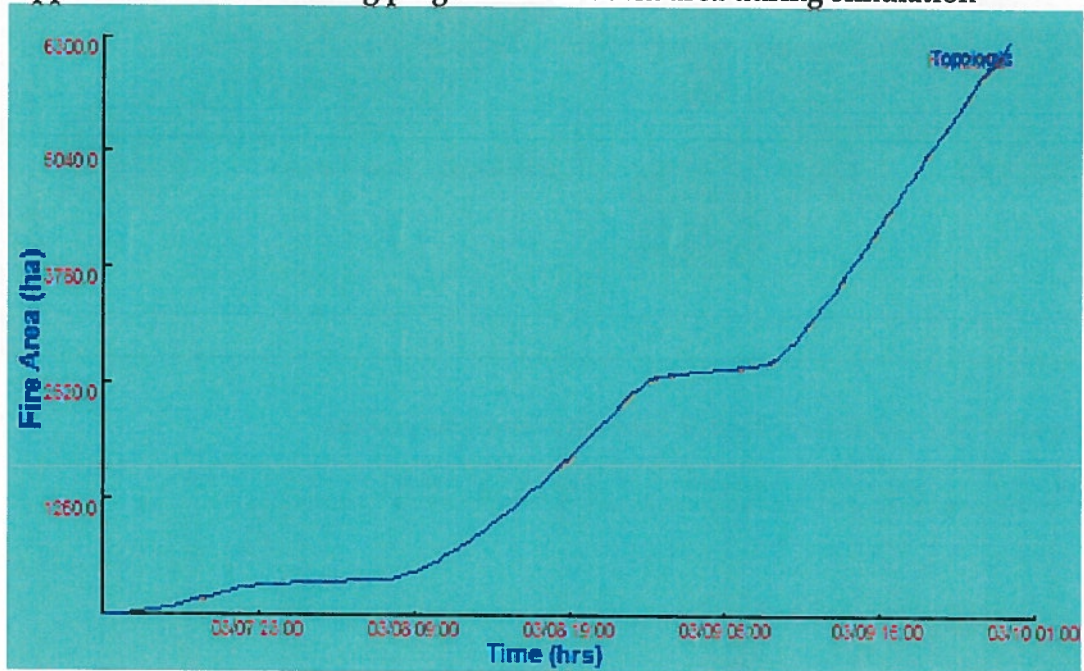




Appendix 3: 3-D view of the landscape with fireline intensity draped over it

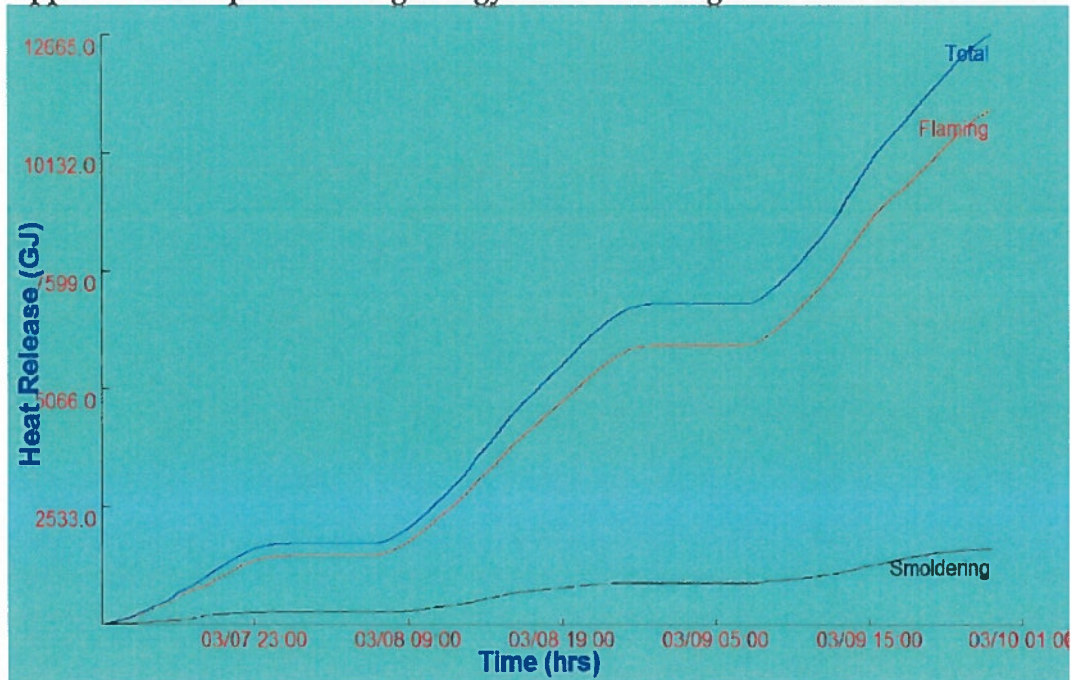


Appendix 4: Chart showing progression of burnt area during simulation





Appendix 5: Graph indicating energy released during FARSITE simulation



Appendix 6: Interface of FARSITE showing the Landscape File Generation dialog box

