MODELLING FOREST FIRE BEHAVIOUR AND MAPPING CARBON EMISSION IN THE LUDIKHOLA WATERSHED, GORKHA DISTRICT, NEPAL

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ABSTRACT: Forest fires have become intense and more frequent in the last few decades all over the world. The profound impacts of forest fires have on atmospheric chemistry, biogeochemical cycling and ecosystem structure have led to the need to understand their behavior. Forest conditions, topography and weather greatly influence forest fire behavior and thus determine fire severity and consequently carbon emission. The estimation of carbon emission from forest fires is crucial for improving our understanding of the carbon cycle dynamics in order to develop strategies to curb the global warming - climate change problem. Previous studies have shown that modeling forest fire behavior can accurately give a good estimate of carbon emissions. The concentration of forest fire emissions varies spatially from one fire event to another as these emissions are a function of fire intensity, amount of biomass burned, and prevailing weather conditions. Therefore, this study is aiming at modeling forest fire behavior, and developing a method to estimate carbon emission in the rugged terrain of Nepal using 3 fire events that occurred in April 2008. A state of the art fire behavior model, FARSITE was used to simulate fire behavior in a spatially and temporally explicit manner taking into account the fuel, topography and prevailing weather in the Ludikhola watershed situated in the Gorkha district of Nepal. A WindNinja model was used to derive local winds influenced by vegetation and topography in the area. A combined approach involving a FARSITE *model* output parameter i.e. fire line intensity and a carbon emission estimation model developed in this research. The model was used to estimate fire induced carbon emission. The simulations were validated with the real mapped fire scar. The simulations using both uniform and spatially varying wind data, estimated the size of the real burned area with accuracies ranging between 78% and 96% for the three fire events were analysed.

1. INTRODUCTION

Forest fires are vital for the survival of forest ecosystems as they recycle nutrients, regulate the density and composition of young trees, and also create and shape wildlife habitat (Noss *et al*., 2006). However, they also can be destructive to vegetation, human life and infrastructure. For example, there were wildfire outbreaks in Russia that began in July 2010 after an intense heat wave, destroyed approximately 900,000 hectares of land and left more than 2,000 people homeless. Forest fires, due to their frequency of occurrence and the magnitude of its effects on the environment, health, economy and security. They have increasingly become a major subject of concern for decision makers, fire-fighters, researchers, and citizens in general. One of the major consequences of forest fires is the atmospheric emission of various environmentally significant gases and solid particulates that contribute to local, regional, and global phenomena in the biosphere. Smoke pollution due to forest fire events is an important public health issue to the local community, whilst the emission of greenhouses such as CO_2 is an important environmental issue to the local, regional and global community. These and other various effects of fire have led to the modelling efforts by fire scientists in order to understand the behaviour of fire propagation in various land cover types.

Forests play a substantial role in the carbon cycle as they act as a major reservoir of global terrestrial carbon (Gibbs *et al*., 2007). A report by FAO (2007), states that terrestrial ecosystems currently hold 2,200 GtC, with about 1,200 GtC of this carbon residing in forests. Several studies have revealed that the net carbon uptake by forests accounts for more than 18-25% of the global terrestrial carbon (Choi and Chang, 2006; Gibbs *et al*., 2007). Even though forests are recognized as large sinks for carbon, when subject to fire they release large amounts of carbon into the atmosphere instantly. It is estimated that, globally, total gas emissions from forest fires is about 4.5 Pg C year–1, which represents more than half the total emissions due to fossil fuel combustion (IPCC, 2007). Thus, it is evident that forests play a key role in stabilizing the atmospheric concentration of greenhouse gases.

Greenhouse gases (GHGs) are the gases that trap and re-radiate heat (infrared radiation) in the atmosphere, in a process known as the greenhouse effect. These gases include carbon dioxide (CO_2), methane (CH_4) and water vapour (H_2O). They occur naturally and serve the purpose of warming the earth. However, anthropogenic activities have resulted in the emission of large additional amounts of these gases into the atmosphere. CO_2, which results from burning fossil fuels and forest fires, is one of the major contributors to the greenhouse effect and subsequently to global warming. According to UNEP (2007), the concentration of CO_2 has increased considerably over recent decades due to fossil fuel combustion, industrial processes, waste water treatment and deforestation. Several studies revealed that CO_2 concentration has increased from 278ppm in the pre-industrial era (AD 1000-1750) to 379ppm in 2005 at an average of 1.9ppm per year (IPCC, 2007; UNEP, 2007). The greenhouse effect of CO_2 in the atmosphere poses a risk of increase in atmospheric temperature and, subsequently, global warming. This process has a great influence on climate change. This is one of the most pressing problems that the earth is presently facing. The concentration of forest fire emissions varies spatially from one fire event to another as these emissions are a function of fire intensity, amount of biomass burned, and prevailing weather conditions. A large component of smoke from forest fires is CO_2. According to Zhanqing *et al*., (2005), a complete and accurate accounting of forest fire induced carbon dioxide emissions is important because CO_2 contributes to climate change. Dwomoh (2009) supports this idea, by stating that, "accurate estimation of carbon emission from forest fires is crucial for improving our understanding of the climate-carbon cycle interaction".

Previous studies on carbon emission from forest fires were made using ground-based fire data sets. These relied on average burned area, average biomass levels and estimates of fractions of biomass consumed during fire (Kasischke *et al*., 2005). However, depending on weather conditions and topography of the area, wildfires burn various types of fuel. Furthermore, these fuels burn differently with different intensities. This results in large spatial and temporal variations in burnt fuel which are directly related to carbon emission. Therefore, remote sensing is important as it can provide spatial and temporal fire information to improve fire emission estimations because it provides data on burnt area, snapshots of fire dynamics and spatial heterogeneity. Spatially explicit fire behaviour simulation models that can be incorporated in GIS environment have been developed which allow the prediction of fire spread and intensity across landscapes (Finney, 2004). Knowledge of fire intensity on various forest cover types enables the determination of biomass consumed during a fire and, subsequently, the CO_2 emissions.

In Nepal, forests cover 39% of the total land area of the country; however this area is estimated to be decreasing at an annual rate of 1.7% (Goldammer, 2000). According to Acharya and Dangi (2009), the rate of forest degradation (8%) is higher than that of deforestation (1.6%). In Nepal, there are five major climatic regions classified based on altitude namely, the Terai, Siwaliks, middle mountains, high mountain and high Himalayas. Forest fires occur annually in these regions, during the dry season from February to May. The tropical and sub-tropical hilly forests in the Terai and Middle mountain region are subject to frequent wildfires as well as human induced fire, thus significantly contributing to forest degradation. It is estimated that more than 400,000 ha of forest area in Nepal are burnt annually (IFFN, 2006). However, the government has limited initiatives on the prevention and control of forest fire. According to a TV report by NBS (2002), there is no systematic and complete record of the occurrence of forest fires and affected areas in Nepal. Previous research has shown that accurately modelling forest fire behaviour can give a good estimation of carbon emission hence a state of the art fire behaviour model was used, which takes into account various types of fuels, topography and weather. In this research, the FARSITE fire behaviour model (Finney, 2004), was used to simulate past fires, their intensity and rate of spread, under known prevailing weather conditions. Development of a method that can accurately estimate fire induced carbon emission requires locally applicable tree biomass maps. Therefore, a local biomass map derived from a high resolution image (Geo-Eyes MSS) was used along with fire line intensity maps produced from the FARSITE fire behaviour model to develop a method to model and map the amount of carbon emitted. In fire modelling, it is vital to have accurate information about the fuel status. In this research, an appropriate fuel model was selected from previously developed standard fuel models based on observed vegetation characteristics. In cases where the vegetation characteristics do not match well with the standard fuel models, a custom fuel model can be developed through the adjustment of fuel parameters as observed in the field. The aim of this research is to model forest fire behaviour and subsequently, develop a method to model and map carbon emission from forest fires in the tropical forest of Ludikhola watershed, Gorkha, Nepal.

2. MATERIALS AND METHODS

2.1 Study Area

The Ludikhola watershed area is located in Nepal in the southern part of Gorkha district, between 27°06′29″ to 27°13′15″N and 85°00′00″ to 85°06′30″E. It lies in the Middle Mountain Ecological Zone (Figure 1). There are 41 community forests (CFUGs) covering a total of 3049.12 hectares of forest area, and the remainder of the forest is classified as government and private forests. The climate of the area varies from sub-tropical at lower altitudes to temperate at higher altitudes. The rainy season commences in June and ends in August, with an average annual rainfall of 1972 to 2000 mm. The minimum temperature is 5°C and the maximum is 33°C, the hottest and driest days fall in the months of March, April and May. Generally, the area is mountainous with an altitude range of between 576m to 1560m. On average, 61% of the land is steep sloping (slope range of 30-60%) and the remaining land has less than 30% slope. The watershed has four major rivers that run within and along it, namely Chepe, Daraudi, Marsyangdi and Budhi Gandaki. Ludikhola watershed is characterised by upper tropical to sub-tropical lower forests. It bears Sal (*Shorea robusta*), Schima (*Schima wallichi*), and pines as dominant species followed by a few other species like Chestnut (*Castanopsis indica*), *Ficus racemosa*, *Terminalia chebula*, and *Bombax ceiba* (ANSAB, 2009).

2.2 Research Methods

The flowchart in Figure 2 shows the outline of the methods followed in this research starting from the preparation of the model inputs. The expected outputs to answer the proposed research questions are highlighted. The study was divided into two main parts i.e. fire behaviour modelling and above ground biomass/carbon estimation and mapping. These were then coupled for estimating and mapping of carbon released from forest fires.

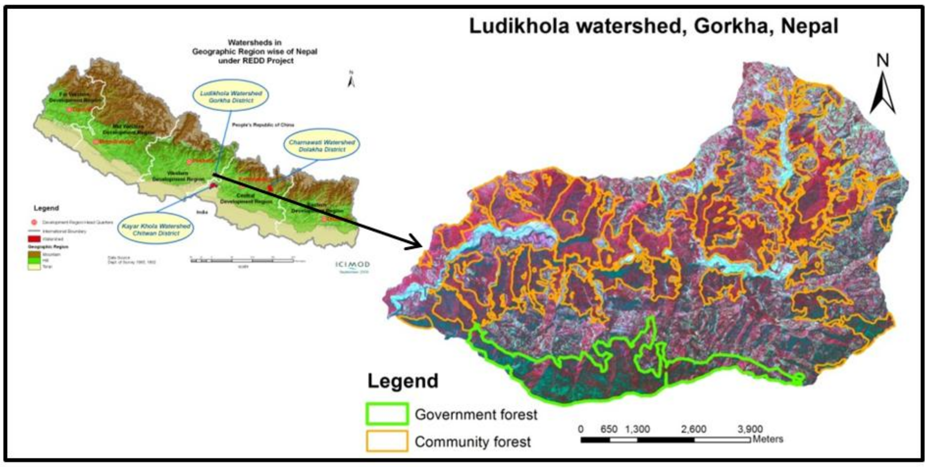

Figure 1: Location of the study area.

A GeoEyes multispectral image with a 2 metre resolution taken in 2 November 2009 (0530hrs GMT) was used for this study. Choice of the image was based on its suitability for the research because of the high resolution. The image was used for the classification of forest cover types and consequently the derivation of canopy cover, biomass/carbon distribution and fuel type maps. An ASTER scene taken on the 11th of May 2008 was used to extract a burned area map for use in model evaluation. MODIS active fire data was used for the identification of ignition points. The data which was used in this study and the sources are listed in Table 1.

Table 1: The list of data used in the study

Data	Source
Weather data (daily temperature, rainfall, humidity, wind speed, wind direction)	Kathmandu Meteorology department
Topography (slope, aspect, elevation)	DEM of the Ludikhola watershed provided by ICIMOD
Canopy cover percentage	Field estimation using a densiometer
Forest cover map	Object oriented classification of Geo-Eye imagery
Fuel models	Selection from the standard fuel models (Scot and Burgan, 2005)
Biomass estimation (tree DBH, height)	Field estimation
Fire scar image	Aster image (11May 2008) provided by ICIMOD
Ignition points	MODIS ignition points, community forest representatives, ground observation

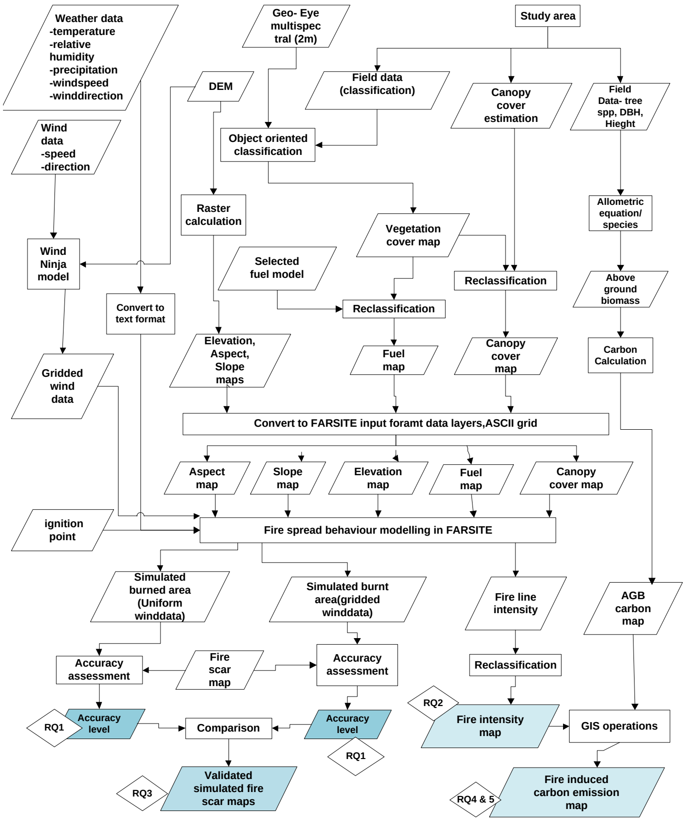

Figure 2: Research Method.

3. RESULTS AND CONCLUSIONS

Forest fire behaviour modelling using the FARSITE fire spread model (Finney, 1998) can be applied well in the tropical forests that lie in the mountainous of the Ludikhola watershed in Nepal. The high resemblance of the pattern of spread and shape of the simulated fire scars to the observed fire scar has indicated the applicability of the model in the study area. This research also proved the applicability of the FARSITE model outputs in the development of a method to estimate fire induced carbon emission. It was found that high intensity fires result in the emission of larger amounts of carbon as compared to low intensity fires. As with other previous studies, cover types rich in carbon density emit less carbon whilst those with less carbon emit more due to the shielding effect of the canopy. The validation of the carbon emission estimation model was not the focus of this study because of lack of empirical data. However, the results from this study provide the necessary knowledge on interactions between fire intensity, biomass density and carbon emission. Based on the results and discussion, the following specific conclusions were reached for each research question.

Does the use of spatially varying wind data provide a significantly better approximation of the observed fire scars than the use of uniform wind data?

Although, the use of spatially varying wind data results in higher accuracy approximations of the observed fire scars than spatially uniform wind data, statistically, the results are not significantly more accurate. Statistical analysis of the differences in the results of the model simulations using ANOVA, shows that there is no significant difference ($\alpha = 0.05$) between the proportions of the observed fire scar simulated using gridded wind data and spatially uniform wind data. Therefore, in this research we reject the alternative hypothesis; the use of spatially varying wind data does not significantly explain fire spread more accurately than the use of spatially uniform wind data.

How accurate is the FARSITE fire spread model in simulating the burnt area for the April 2008 fires?

The FARSITE fire spread model obtained high accuracy values ranging between 78 to 96% in model validation using real April fire scar maps (Figure 3), on the incorporation of both spatially uniform wind data and spatially varying wind data. However, there was one fire event simulation which had a very low accuracy of 17% on the application of uniform wind data but, significantly improved to 78% on the use of spatially varying wind data. Table 2 presents the summary of the accuracy assessment.

Table 2: Summary of the accuracy assessment

	Uniform wind approximation (%)	**Gridded wind approximation (%)**
20 April 2008 fire	17	78
26 April 2008 fire	81	96
28 April 2008 fire	82	90

In this research, the FARSITE fire spread model succeeded in approximating the April 2008 observed fire scars by more than 75%, in both model scenarios incorporating spatially uniform wind data and spatially varying wind data. The fire scar simulations exhibited percentage agreement with the observed fire scar ranging from 78% to 96%. There was only one exception, where fire scar simulation of the 20th April fire with the incorporation of uniform wind data only managed to approximate 17% of the observed fire scar. Therefore, we accept the alternative hypothesis, which means that the FARSITE fire spread model approximates the observed fire scar by more than 75%.

How is the fire line intensity distributed within the simulated fire scar?

The fire events simulations agreed well with the observed of fire intensity in the study area. Generally, low intensity fires occurred in high density forests, whilst high intensity fires occurred in low density forests.

How much carbon was emitted from different forest cover types during the April 2008 fires in the study area?

The amount of carbon emitted per cover type was 626Mg in shrub land, 10404Mg in low density forest, 516Mg in medium density forest and 1370Mg in high density forest. In terms of the amount of carbon emitted per cover type per hectare, 869Mg.ha^{-1} was released from the shrub land, 4624Mg.ha-1 from low density forest, 573Mg.ha^{-1}from medium density forest and 608Mg.ha^{-1} from high density forest. On average, 1669Mg.ha^{-1} of carbon was emitted (Figure 5) from the three fire scars simulated. The low density forest emitted the highest amount of carbon, whilst the medium density forest emitted the lowest amount of carbon.

What is the overall amount of carbon emitted?

The total amount of carbon emitted (Figure 5) from the April 2008 forest fires was 12916Mg, which accounts for 7% of the total sequestered carbon (Figure 4) in the Ludikhola watershed.

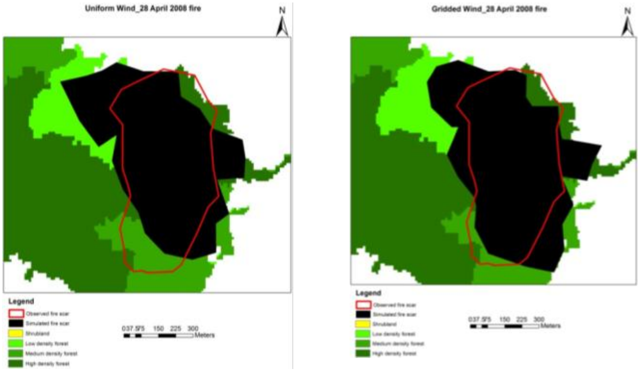

Figure 3: Example of the simulation of fire perimeter using uniform wind data and gridded wind data.

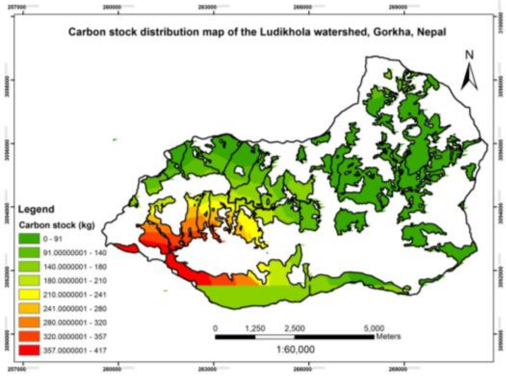

Figure 4: Carbon stock map of Ludikhola watershed

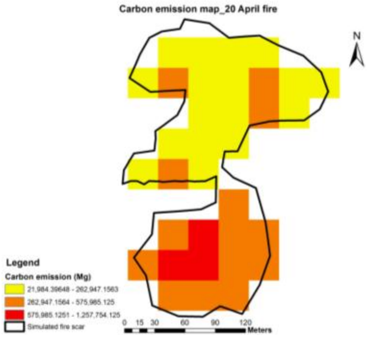

Figure 5: Example of the spatial distribution of carbon released by the 20th April fire

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