FIRE INDUCED CARBON EMISSION FROM TROPICAL MIXED BROAD LEAF FOREST OF NEPAL

A THESIS SUBMITTED TO THE

CENTRAL DEPARTMENT OF ENVIRONMENTAL SCIENCE

INSTITUTE OF SCIENCE AND TECHNOLOGY

TRIBHUVAN UNIVERSITY

NEPAL

FOR THE AWARD OF

DOCTOR OF PHILOSOPHY

IN ENVIRONMENTAL SCIENCE

BY

KRISHNA BAHADUR BHUJEL

FEBRUARY, 2020

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KRISHNA BAHADUR BHUJEL

FEBRUARY, 2020

DECLARATION

Thesis entitled **"Fire Induced Carbon Emission from Tropical Mixed Broad Leaf Forest of Nepal"** which is being submitted to the Central Department of Environmental Science, Institute of Science and Technology (IoST), Tribhuvan University, Nepal for the award of the degree of Doctor of Philosophy (Ph.D.) is a research work carried out by me under the supervision of Professor Dr. Rejina Maskey Byanju, Central Department of Environmental Science, Tribhuvan University and co-supervision of Dr. Ambika Prasad Gautam, Kathmandu Forestry College, Kathmandu.

This research is original and has not been submitted earlier in part or full in this or any other form to any university or institute, here or elsewhere, for the award of any degree.

Date: ....

Krishna Bahadur Bhujel

RECOMMENDATION

This is to recommend that **Mr. Krishna Bahadur Bhujel** has carried out the research entitled **"Fire Induced Carbon Emission from Tropical Mixed Broad Leaf Forest of Nepal"** for the award of Doctor of Philosophy (Ph.D.) in **Environmental Science** under our supervision. To our knowledge, this work has not been submitted for any other degree.

Mr. Bhujel has fulfilled all the requirements laid down by the Institute of Science and Technology (IoST), Tribhuvan University, Kirtipur for the submission of the thesis for the award of Ph.D. degree.

………………………………

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LETTER OF APPROVAL

Date: 05/10/2020

On the recommendation of supervisor **Prof. Dr. Rejina Maskey Byanju** and co-supervisor **Dr. Ambika Prasad Gautam**, this Ph.D. thesis submitted by **Mr. Krishna Bahadur Bhujel,** entitled **"Fire Induced Carbon Emission from Tropical Mixed Broad Leaf Forest of Nepal"** is forwarded by Central Department Research Committee (CDRC) to Office of the Dean, Institute of Science and Technology (IoST), Tribhuvan University (TU).

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....

Krishna Bahadur Bhujel

February, 2021

ABSTRACT

Forest fire is emerging as a major environmental issue across the world. In Nepal, substantial forest area, biomass and carbon are lost due to fire. The high value lowland forests of Nepal are more vulnerable to fire. However, in Nepal, there are limited studies on estimation of biomass loss and carbon emission due to forest fire. Thus, the present research was carried out to estimate forest fire area in different ecological regions of Nepal, and biomass loss and carbon emission from the Tropical Mixed Broad-leaved Forest of Nawalparasi District. The fire drivers were identified using participatory approaches and were prioritized by scoring method. For this purpose, six Focus Group Discussions, 10 Key Informant Interviews and five Consultation Meetings were performed. For estimating biomass loss and carbon emission, DBH and height were measured in 92 sample plots in the four community forests selected purposively based on fire vulnerability and topography ensuring representation of the Lower Tropical Mixed Broad-leaved Forest, Hill Sal Forest and Riverine Forest. Forest fire incidences and burnt area for 2001-2017 were acquired from MODIS fire data. The burnt and non-burnt area were delineated and analyzed in GIS. Forest biomass and carbon emission were estimated using allometric equation. Loss and damage of biomass was estimated using the stock difference method. Data related to road networks, settlements and topography were obtained from the Survey Department, Government of Nepal, forest type data were acquired from Department of Forests and Soil Conservation and climate data were obtained from the Department of Hydrology and Meteorology, Government of Nepal. The results revealed 29,24,691.05 ha forest (1,72,040.65 ha/yr) to be damaged in Nepal from 2001 to 2017. In Nawalparasi District, 3151.05 ha forest per year were found to be damaged. Among the forest types, the Hill Sal Forest was the most vulnerable in compared to the Lower Tropical Mixed Broad-leaved Forest and Riverine Forest. The study revealed 20 forest fire causing drivers; among them, eight drivers, i.e. precipitation, forest distance from road, elevation, forest fuel, forest distance from settlement, temperature, slope and aspect were identified as the major ones. In terms of emission, 1108 tons/year carbon was found to be emitted due to forest fire in Nawalparasi District that is equivalent to approximately 4066 t CO_2, 2581 t CO and 1474 t CH_4.With respect to plant forms, higher (>90%) damage was found in leaf-litter, herbs and grass as compared to trees (0.01-0.4%). These findings are useful for sustainable forest fire management in the lowland of Nepal and in the area having similar ecological and socio-economic conditions.

Keywords: Active fire data, Burnt area, Biomass loss, Carbon emission, Fire drivers

LIST OF ACRONYMS AND ABBREVIATION

AGB	Above Ground Biomass
AVHRR	Advanced Very High Resolution Radiometer
BD	Biomass Density
BE	Burning Efficiency
CBD	Convention on Biological Diversity
CDES	Central Department of Environmental Science
CF	Community Forest
CFUGs	Community Forest User Groups
CSR	Cumulative Severity Rating
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
DFO	Divisional Forest Office
DFRS	Department of Forest Research and Survey
DHM	Department of Hydrology and Meteorology
DoFSC	Department of Forests and Soil Conservation
EF	Emission Factor
FECOFUN	Federation of Community Forestry Users, Nepal
FGD	Focus Group Discussion
FUC	Forest User Committee
GeoTIFF	Geo-referenced Tagged Image File Format
GFED	Global Fire Emissions Database Format
GFMC	Global Fire Monitoring Center
GHGs	Green House Gases
GIS	Geographic Information System
GMST	Global Mean Surface Temperature
GWFT	Glossary of Wildland Fire Terminology

GXM	Great Xing' s Mountains
HSF	Hill Sal Forest
IFFN	International Forest Fire News
IPCC	Intergovernmental Panel on Climate Change
ISDR	International Strategy for Disaster Reduction
KII	Key Informant Interview
LTSMBF	Lower Tropical Sal Mixed Broad-leaved Forest
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MoFE	Ministry of Forests and Environment
NASA	National Aeronautics and Space Administration
NTFP	Non Timber Forest Product
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RF	Riverine Forest
TISC	Tree Improvement and Silviculture Component
TU	Tribhuvan University
UNFCCC	United Nations Framework Convention on Climate Change

LIST OF SYMBOLS

ß	Fraction of biomass consumed in the burn
CO_2	Carbon dioxide
Gt	Giga-ton
ha	Hectare
p	Wood specific gravity (g cm^{-3})
USD	United State's Dollar
e	Error factor
km	Kilometer
m	Meter
Mg	Megagram
m^3	Cubic meter
Pg	Petagram
R^2	Coefficient of determination
Tg	Teragram
X	Independent variable
Y	Dependent variable

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CHAPTER 1

1 INTRODUCTION

1.1 Background

Fire is the process that results when three components, i.e., fuel, oxygen and heat combine together. These three components of fire are known as the “fire triangle”, which is a simple way of understanding the three components required to set fire (Fig. 1). A fire cannot occur in the absence of anyone component of the fire triangle. Thus, a fire can be extinguished by removing one of the components of the fire triangle.

The forest fire varies according to the landscape. At the local landscape level, three major principle factors, *viz*. weather, fuel and topography play a crucial role in forest fire occurrence (Pyne *et al.*, 1996). At the regional or global landscape level, climate, vegetation and land use pattern play an important role in forest fire occurrence (Bowman *et al.*, 2009).

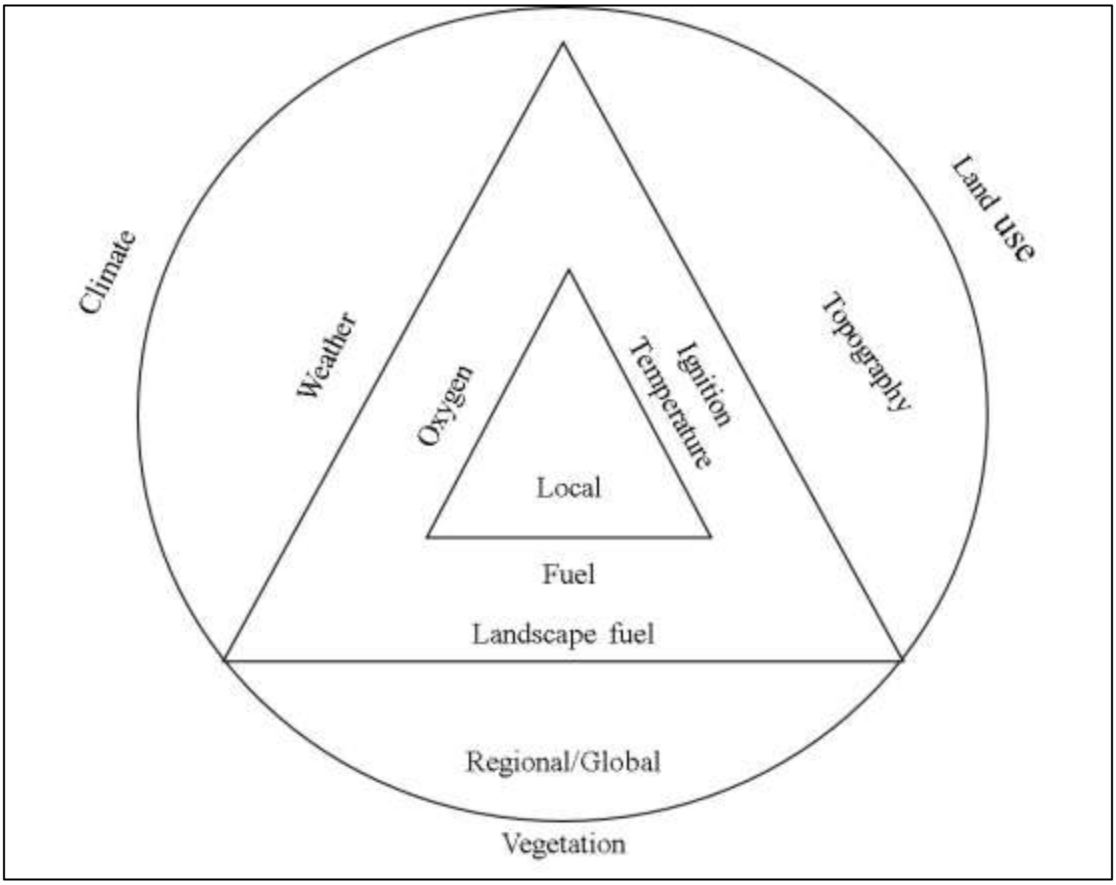

Figure 1: Various components of fire triangle at different landscapes (Adapted from Bowman *et al.*, 2009)

According to the Glossary of Wildland Fire Terminology (GWFT) (2008), there are three basic types of the forest fire, namely, surface fire, ground fire and crown fire. Surface fire burns only surface materials, specifically litter and debris. This type of fire is manageable and causes least damage to the forest. Likewise, a ground fire occurs due to deep accumulation of humus, peat and dead vegetation, which burns and moves slowly. This type of fire is challenging to suppress. Similarly, crown fire generally burns upto the uppermost part of trees. This type of fire is the most intense and dangerous.

Forest fire occurs due to natural and anthropogenic causes. Natural causes include high atmospheric temperatures, low precipitation, lightning, accumulation of forest fuel and topographic features that offer favorable circumstances to set fire (Flannigan *et al.*, 2005; Holden *et al.*, 2009). Anthropogenic causes include the distance of forest from road and settlement, wildlife predators, fuel-wood collector, campfire, burning matches, cigarette butts and grass-cutters (Guo *et al.*, 2016). Among the natural causes, the climatic factor is the prime driver for large regional fires (Bowman *et al.*, 2009). For forest fire occurrence, the variation of climatic factors is more sensitive as compared to terrain complexity and fuel pattern (Cary *et al.*, 2006). Likewise, Parisien and Moritz (2009) have reported that forest fire range shifts according to changing climatic conditions. For example, increased temperature results increase in forest fire occurrences. Moreover, annual and daily meteorological patterns can heavily influence forest fire occurrence during the active fire season (Martin & Birk, 2010). The global mean surface temperature has been reported to be increased by an average 0.87°C during 2006-2015 in comparison to the 1850-1900 period resulting in an increase in forest fire occurrence (IPCC, 2014).

According to Leimgruber *et al.* (2011), the Tropical Forest of South and South-east Asia is extensively dry due to variation in monsoon. Likewise, Charles and Steven (2012) have reported the influence of precipitation on forest fire occurrence in the Eastern United States. Similarly, in the Yunnan Province of South-west China, Chen *et al.* (2014) have reported precipitation as the major influential factor in forest fires during the dry season. In the Boreal Forests of North-east China, the forest fire occurrence has been reported to have positive correlation with temperature and negative correlation with precipitation (Chen *et al.*, 2014; Liu *et al.*, 2012). The similar results have been reported in the Central Siberia (Ponomarev *et al.*, 2016), Eastern Iberian Peninsula (Pausas, 2004), in the Western USA (Littell *et al.*, 2009) and Galicia Spain (Martin & Birk, 2010). Likewise, precipitation has strong influence on forest fire occurrence in India (Ahmad *et al.*, 2017; Prasad *et al.*, 2008). In Nepal, the climatic variable is the primary driver for forest fire occurrence (Khanal, 2015; Matin *et al.*, 2017).

With respect to the topographic drivers, aspect, elevation and slope are the major forest fire drivers. In Central Spain, the topographic factor has been reported as an important driver for forest fire occurrence (Romero *et al.*, 2008). Moreover, Wood *et al.* (2011) have reported elevation and aspect as the important predictors for forest fire occurrence in South-west Tasmania, Australia. Similarly, Holden *et al.* (2009) have reported that forest fire is influenced by the biophysical gradients, particularly, solar radiation and topographic moisture. Likewise, Estes *et al.* (2017) have depicted that the topographical complexity strongly influences forest fire in the Klamath Mountains, Northern California, USA. However, Collins *et al.* (2009) have revealed that forest fire is self-limiting at upper elevation in the Sierra Nevada Mixed Conifer Forest. The topography and fuels have strong influence on forest fire occurrence during the warmer climatic conditions (Bradstock *et al.*, 2010). Similar results have been observed by Taylor and Skinner (1998) in the Klamath Mountains of California, USA.

Forest fuel that includes dead and live woody or non-woody biomass is another important natural driver of forest fire occurrence (Sandberg *et al.*, 2001). Dead and fallen woody materials, litter, grasses, herbs and shrubs are the most common surface fuels, often the most hazardous for fire occurrence (DeBano *et al.*, 1998). Similarly, canopy fuels are burnable aerial biomass primarily composed of tree branch-wood and foliage such as arboreal mosses, lichens and other hanging dead materials (Reinhardt *et al.*, 2006). In forest, ladder fuels such as small trees or tall shrubs and climbers provide vertical continuity from the surface to the crowns of tall trees, are the most hazardous fuel (Stephens *et al.*, 2009). In addition, the forest fire is affected by vegetation types (Salis, 2008). According to Nemani *et al.* (2003) and Zhao and Running (2010), accumulation of fuel affects the forest fire.

In connection to the anthropogenic drivers, human-induced fires are the primary drivers of the forest fire, which have been reported to be 10 times higher than the forest fire incidences due to natural causes (Bowman *et al.*, 2011; González *et al.*, 2015; Lewis *et* *al.*, 2015). Bowman *et al.* (2011) and González *et al.* (2015) have reported that most of the human-induced fires are accidental, usually caused by carelessness or inattention by wood collectors, campers, hikers, travelers and garbage burners. Among the anthropogenic factors, the forest distance from settlement and road have been reported as the major drivers of forest fire occurrence in the Boreal Forest of China (Guo *et al.*, 2015; Guo *et al.*, 2016). The forest distance from the road has been reported to be highly correlated with the severity of fire occurrence in Golestan, North-east Iran (Abdi *et al.*, 2016). Likewise, Wallenius *et al.* (2004) have reported that the expansion of human settlements and increase in population had lead to fire occurrence in the Boreal Forest of the Northern Europe. The socio-economic development and vegetation of the world have been directly affected by the forest fire, which has been projected to be further increased at the landscape level in the next century (Andela & van der Werf, 2014).

The forest ecosystem plays an important role in the global carbon cycle and carbon storage in vegetation and soil (Pan *et al.*, 2011). According to FAO (2007), the terrestrial ecosystems currently hold 2,200 Gt (Gigaton) carbon. Out of this, 1,200 Gt carbon is residing in forests. Approximately, 60% of carbon is stored in global forests (FAO, 2005). About 50% of carbon is stored in the Tropical Forests and 50% in the soil (IPCC, 2000). Although, forests are recognized as the large carbon sinks, they release huge amounts of carbon into the atmosphere, if subjected to fire.

Globally, around 345 million hectare forest burns every year, resulting in a large quantity of carbon release into the atmosphere (Randerson *et al.*, 2012). For instance, van der Werf *et al.* (2010) have reported an average 2.0 Pg (petagram) annual carbon emission from biomass burning during the periods from 1997 to 2009. Similarly, van der Werf *et al.* (2017) have reported global mean 2.2 Pg annual carbon emission from 1997 to 2016. It indicates that globally, fire induced carbon emission is in increasing trend. Moreover, over half of the total carbon has been reported to be emitted due to fossil fuel combustion (IPCC, 2007). In the Mato Grosso of Brazil, Soares *et al.* (2009) have reported that one hectare of burnt forest releases around 117.0 tons of CO_2, 8.1 tons of CO and 0.68 tons CH_4. Likewise, in China, Zhang *et al.* (2016) have reported an annual emission of 0.04 Tg (Teragram) to 7.22 Tg carbon due to forest fire from 1988 to 2012. Similarly, Badarinath and Vadrevu (2011) have reported an annual emission of 6.34 Tg CO_2 from forest biomass burning in India. In Nepal, on average, 1669 Mg/ha annual carbon emission due to forest fire has been reported from the forest of Ludikhola Watershed of Gorkha District (Sibanda, 2011).

With respect to the loss and damage, it has been reported that forest fire is causing adverse impacts on the environment (UNFCCC, 2012). In the South-east Asia, EEPSEA/WWF (1998) has reported forest damage worth more than USD 4 billion, due to forest fire. However, Noss *et al.* (2006) have revealed that forest fire plays a vital role in restoring forest ecosystems through proper management of forest fire.

In context of Nepal, 1,159.65 million tons (194.51 t/ha) of above-ground air-dried biomass and 1,054.97 million tons (176.95 t/ha) of carbon stock have been estimated (DFRS, 2015). According to Sharma (2006), valuable timber and non-timber forest resources, natural regeneration and planted forests are damaged due to forest fire. Annually, approximately, 4,00,000 ha forest has been reported to be burnt in Nepal (Bajracharya, 2002). Similarly, Parajuli *et al.* (2015) have reported that the number of forest fire incidences is increasing. Moreover, Khanal (2015) have reported that 375,000 ha forests burnt during the period from 2001 to 2015. Furhtermore, Matin *et al.* (2017) have observed that 18 districts of Nepal including Nawalparasi are at very high risk of fire. However, the most of the preceeding studies (Bajracharya, 2002; DFO, 2013; DFRS, 2015; Khanal, 2015; Matin *et al.*, 2017; Parajuli *et al.*, 2015; Sharma, 2006) seem to be limited within forest fire risk analysis and calculation of forest fire occurrence and burnt area without considering identification of forest fire drivers, their contribution to fire occurrence and estimation of the loss of biomass and carbon emission in the Tropical Mixed Broad-leaved Forest. Therefore, this study was carried out with the aim of assessing forest fire drivers, their contribution to forest fire, biomass loss and carbon emission.

1.2 Rationale

Forest is an important natural resource, which is degrading due to various natural and anthropogenic causes (Flannigan *et al.*, 2005; Guo *et al.*, 2016). Among them, fire is one of the major causes of forest degradation. At the global level, forest fire has been substantially increased in recent years, adversely affecting environment, health, economy and public security (Miranda *et al.*, 2012). Similarly, Tropical Forests in mainland Asia were highly vulnerable to fire (van der Werf *et al.*, 2008). Thus, in the present context, forest fire has been emerging as a challenging issues across the world.

At the regional level, the Tropical Rain-forests of the South America, Asia, Australia and Africa have been reported to be influenced by fire (Juárez *et al*., 2017). Similarly, the high-value forests of Iran, China and India have been reported to be vulnerable due to forest fire (Abdi *et al*., 2016; Ahmad *et al*., 2017; Chen *et al*., 2014). In context of Nepal, forest fire has been increasing due to natural and anthropogenic causes making high-value forests vulnerable (Bajracharya, 2002; DFO, 2013; DFRS, 2015; Khanal, 2015; Kunwar & Khaling, 2006; Matin *et al*., 2017; Parajuli *et al*., 2015).

Moreover, forest fire has been affecting forest biomass and carbon stock. Around 15% of the global forest biomass has been reported to be lost annually due to forest fires (Liu *et al*., 2019). At the regional level, forest biomass burning has been increasing affecting socio-economy and environment (Bowman *et al*., 2017; Flannigan *et al*., 2013; Street *et al*., 2003). In the South-east Asia, forest resources worth around USD 4 billion has been reported to be damaged due to forest fire (EEPSEA/WWF, 1998). This loss of biomass ultimately results into increased carbon emission. At the global level, around 11% of carbon emission has been reported to be increased in the period between 1997 and 2016 (van der Werf *et al*., 2017). Similarly, in China (Zhang *et al*., 2016) and India (Badarinath & Vadrevu, 2011) have also experienced an increase in carbon emission due to forest fire.

In context of Nepal, 18 districts have been reported to be at very high risk of forest fire (Matin *et al*., 2017). Among them, nine districts including Nawalparasi are located in the lowland of Nepal, which is rich in high-value forest stand. In Nawalparasi district, there are five types of forest, i.e., Lower Tropical Sal Mixed Broad-leaved Forest, Hill Sal Forest, Riverine Forest, Schima-Castanopsis Forest and Chirpine Broad-leaved Forest. In these forests, around 91% of areas are covered by the high-value Lower Tropical Sal Mixed Broad-leaved Forest, Hill Sal Forest and Riverine Forest, which are economically, ecologically and environmentally important. These forests have been reported to be more vulnerable to fire (DFO, 2013; ICIMOD, 2016). Thus, for sustainable forest fire management at global, regional and local level, identification and understanding of forest fire drivers are important. However, preceding works pertaining the forest fire in Nepal have mostly covered fire risk analysis (Matin *et al*., 2017; Parajuli *et al*., 2015) and burnt area estimation (Bajracharya, 2002; Khanal, 2015). In this context, identification of forest fire drivers, their contribution to fire occurrence, estimation of the loss and damage of biomass and carbon emission is crucial for sustainable forest management. Thus, forests of Nawalparasi district was selected as the representative Tropical Mixed Broad-leaved Forests of Nepal. The present research would be useful in forest fire control, which will ultimately help in restoring the forest ecosystem with increased biomass and carbon stock and reduced carbon emission supporting to Reducing Emissions from Deforestation and Forest Degradation (REDD+) program of Nepal.

1.3 Objectives

1.3.1 General objective

The general objective of the study was to assess the extent of forest fire carbon emission in the Tropical Mixed Broad-leaved Forest of Nawalparasi district in Nepal.

1.3.2 Specific objectives

The specific objectives of the study were:

1. To identify the major forest fire drivers that contribute to fire occurrence.
2. To estimate the amount of carbon emitted due to forest fire and its possible contribution in emission.
3. To assess the loss of forest biomass and carbon due to forest fires.

CHAPTER 2

2 LITERATURE REVIEW

Forest fire is associated with various fire drivers. The contribution of fire drivers varies spatially and temporally. The forest fire has its implication on biomass loss and damage, and carbon emission. In this connection, the various preceding studies published in the scientific arena have been reviewed in this section.

2.1 Forest fire incidences and burnt area

The forest fire incidences and burnt area have been studied at local, regional and global level from various authorises. Several studies have reported to increase the forest occurrence and burnt area (Bajracharya, 2002; Bhujel *et al.*, 2017a; Bhujel *et al.*, 2018b; Chen *et al.*, 2020; EEPSEA/WWF, 1998; Khanal, 2015; Miranda *et al.*, 2012; Parajuli *et al.*, 2015; Randerson *et al.*, 2012; Satendra & Kaushik, 2014). According to Miranda *et al.* (2012), the forest fire has been substantially increased in recent years, adversely affecting environment, health, economy and public security at global level. Globally, about 345-464 Mha forest was recorded burned every year during the period from 1990s to 2000s (Randerson *et al.*, 2012). In the South-east Asia, forest resources worth around USD 4 billion has been reported to be damaged due to forest fire (EEPSEA/WWF, 1998). Similarly, in China, on average, about 0.081-0.125 Mha per annum forest area was burnt in the last two decades (1997-2016) (Chen *et al.*, 2020). In India, around 3.73 million hectares forest get affected by fires annually (Satendra & Kaushik, 2014). In Nepal, annually, approximately, 4,00,000 ha forest has been reported to be burnt in Nepal (Bajracharya, 2002). Similarly, Khanal (2015) have reported that 375,000 ha forests burnt during the period from 2001 to 2015. Moreover, Parajuli *et al.* (2015) have reported that the number of forest fire incidences is increasing. Bhujel *et al.* (2017b) have revealed that the density of forest fire occurrence (0.09/km^2 incidence and burnt area 3.4 ha/km^2) are higher in 2016 compared to the period of 2000-2015 (0.03 incidences and 1.4 ha km^{-2} burnt area) in Terai region of Nepal (Bhujel *et al.* 2018b).

2.2 Forest fire drivers

Forest fire is a phenomenon that occurs due to natural and anthropogenic causes. Forest fire occurrence and its severity vary according to fire drivers. With respect to natural drivers, several studies have identified global forest fire drivers. Among the natural drivers, the climatic driver has been reported to be the cause of increased forest fire (IPCC, 2014; Juárez *et al.*, 2017; Krawchuk *et al.*, 2009; Pausas & Ribeiro, 2013). According to IPCC (2014), Global Mean Surface Temperature (GMST) has increased up to 0.87°C in the period of 2006-2015 relative to the period of 1850-1900, resulting into increase in global forest fire incidences. Similarly, Pausas and Ribeiro (2013) have assessed the productivity of forest fuel due to global warming and reported that productive regions are more vulnerable. Likewise, Krawchuk *et al.* (2009) have assessed the impacts of climate change on global forest fire occurrence in the 21st century and reported that climate change has an impact on forest fire occurrence. Moreover, Juárez *et al.* (2017) have reported that the global climate change has influenced the forest fire occurrence in the tropical rainforests of the South America, Asia, Australia and Africa from 1981 to 2015.

In the regional level, the studies (Charles & Steven, 2012; Leimgruber *et al.*, 2011) have reported the impacts of climatic drivers on forest fire occurrence. In this connection, Charles and Steven (2012) have examined the relationship between climate factor and forest fire occurrence based on the available flammable materials in the different landscapes in the Eastern United States and reported that the intra-annual precipitation variability has strong influences on the forest fire. Similarly, Leimgruber *et al.* (2011) have assessed the relationship between forest fire occurrence and uncertainty of variation of monsoonal climate and observed that Tropical Forests in the South and South-east Asia are more fire vulnerable due to seasonal uncertainty of monsoonal climate variation.

In USA and Canada, earlier studies (Flannigan *et al.*, 2005; Littell *et al.*, 2009; McKenzie *et al.*, 2012; Parisien & Moritz, 2009; Parisien *et al.*, 2014; Westerling *et al.*, 2006) have reported the relation between climate variables and forest fire occurrence. Flannigan *et al.* (2005) have compared climate factors with forest burnt area, terrain complexity and fuel pattern in Canada during the end of 21st century and have reported that forest burnt area and climatic factors are more sensitive to fire than terrain complexity and fuel pattern. Likewise, Littell *et al.* (2009) have assessed the relationship between climate variables and forest brunt area having different vegetation types in the Western United States during the period of 1916-2003 and revealed that climate has strong linkages with forest burnt area. Furthermore, McKenzie *et al.* (2012) have reported that the spatial patterns of stored energy (fuel) and solar energy (weather and drying of fuels) are the major drivers of forest fire in the Western USA. Moreover, Parisien and Moritz (2009) have observed that forest fire range shifts with the changing climatic condition in the United States. Parisien *et al.* (2014) have assessed the influence of environmental drivers on forest fire activity in the Canadian Boreal Forest during the period from 1980 to 2010 and reported that environmental variables influence forest fire occurrence. Similarly, Westerling *et al.* (2006) have evaluated the effects of hydro-climatic and land-surface data on forest fire during 19th and 20th century in the Western United States, since 1970 and shown sudden and marked increases forest fire activity in the mid-1980s, with higher forest fire frequency, longer forest fire durations and longer forest fire seasons.

In countries like Iran, China and India, previous studies (Abdi *et al.*, 2016; Ahmad *et al.*, 2017; Chen *et al.*, 2014) have reported that climatic variables are important drivers to forest fire occurrence. In Iran, Abdi *et al.* (2016) have reported that daily mean temperature and forest distance from roads are the major forest fire drivers. Similarly, Chen *et al.* (2014) have reported precipitation to be the significant fire drivers during 1982-1988 and 1989-2008 in five eco-regions of Yunnan Province, China. In India, Ahmad *et al.* (2017) have depicted that precipitation is the major fire driver among all other environmental parameters contributing to forest fire events from 2005 to 2016. In Nepal, Bhujel *et al.* (2017a) have reported that the temperature and humidity are correlated with forest fire incidences and burnt area in the Nawalparasi district from 2000-2014. Similarly, the occasional precipitation has been significantly correlated ($p<0.05$) with forest fire incidences and burnt area during the period from 2000-2014 in the Nawalparasi district of Nepal (Bhujel *et al.*, 2018a).

In connection to topography, the various studies (Bigio *et al.*, 2016; Holden *et al.*, 2009; Iniguez *et al.*, 2008; Kumar *et al.*, 2015; Wood *et al.*, 2011) have reported that topography is an important forest fire driver which varies according to the characteristics of topographic features. In this connection, Bigio *et al.* (2016) have assessed the influence of aspect and rugged terrain to forest fire frequency in three tributary watersheds of the San Juan Mountains of the South-western Colorado and have revealed that fire frequency varies according to aspect and largest differences between the north and south-facing aspects in the two largest basins. Likewise, Holden *et al.* (2009) have evaluated influence of topography (aspect, elevation, slope and ruggedness) on fire occurrence during the period from 1984 to 2004 in the Gila Wilderness and surrounding the Gila National Forest in New Mexico USA and reported that topographic factor is the major fire driver for forest fire occurrence. Similarly, Iniguez *et al.* (2008) have reported the similar influence of topography on fire patterns in the Santa Catalina Mountains of the South-eastern Arizona. In India, Kumar *et al.* (2015) have assessed the role of topography in forest fire occurrence in the Kangra region of the Western Himalaya and reported that geographical features like aspect, elevation and slope as the major drivers for forest fire occurrence. Likewise, Wood *et al.* (2011) have assessed the role of topography on forest fire occurrence in the Eucalyptus Forest and Rain Forest in the rugged terrain of the South-west Tasmania, Australia and reported that topography plays an important role in mediating the forest fire.

Among other natural drivers, forest biomass (fuel) is an important forest fire driver. The various studies (Alvarez *et al.*, 2013; Arienti *et al.*, 2009; Badarinath & Vadrevu, 2011; Brando *et al.*, 2016; Butler *et al.*, 2007; Chen *et al.*, 2008; Duff *et al.*, 2017; Liu *et al.*, 2008) have reported that the forest fuel is an important fire driver, which plays vital role in forest fire occurrence. In this connection, Alvarez *et al.* (2013) have assessed the relationship between forest fuel and forest fire occurrence in the North East Iberian Peninsula and reported that forest fuel is important fire driver. Similarly, Arienti *et al.* (2009) have revealed the similar result in the Western Boreal Forest of Canada. Likewise, Chen *et al.* (2008) and Liu *et al.* (2008) have observed that the Boreal Forest in China has become highly forest fire vulnerable due to highly loaded fine fuel from the different composition of species ladder and stand age. In India, Badarinath and Vadrevu (2011) have reported the higher accumulation of forest fuel in the Closed Broad-leaved Deciduous Forest and Closed Mixed Broad-leaved Forest making the forests more fire vulnerable. Likewise, Brando *et al.* (2016) have explained that the increases in fine fuel loads likely to create catastrophic fires during dry year. According to Duff *et al.* (2017), the fuel dynamics and complex biotic nature of fuel affects the worldwide fire regimes. Furthermore, Butler *et al.* (2007) have examined the effect of slope on fire speed with vertical fuel array of woody fuels and have reported that the upper limit of heading fire rate of spread depends on the vertical arrangement of fuel in Rome.

With respect to the human-induced fire drivers, the various studies (Adab *et al.*, 2013; Bowman *et al.*, 2011; FAO, 2007; Gralewicz *et al.*, 2012; Lewis *et al.*, 2015; Niklasson & Granström, 2000; Wallenius *et al.*, 2004) have reported that the human-induced drivers like recreation (camping, hiking, hunting), settlement, road and industry to be the major fire drivers. According to Adab *et al.* (2013), forest and grassland of the North Iran are more vulnerable to fire caused by the anthropogenic factors like forest distance from road and settlement. Similarly, Bowman *et al.* (2011) have reported that the anthropogenic activities such as recreation (hiking, camping and hunting), settlement, road and industry as the major forest fire drivers at global level. Likewise, in Canada, Gralewicz *et al.* (2012) have reported that forest fire occurrence is closely related to forest distance from road and settlement. According to FAO (2007), around 80% of the world's forest fire is caused by anthropogenic activities. Similarly, Lewis *et al.* (2015) have reported that human-induced forest fire has increased in the recent years, threatening Tropical Forests across the world. Moreover, Niklasson and Granström (2000) have assessed the fire history and underlying causes in the Swedish Boreal landscape forest and reported that forest fire caused by anthropogenic drivers has increased in the recent years. Furthermore, Wallenius *et al.* (2004) carried out study in the Boreal Forest of the Northern Europe and reported that the historical forest fire occurrence has been strongly affected by human activities such as camping, hiking, hunting, settlement and road.

2.3 Forest fire drivers and fire occurrences

Among the various drivers, contribution to forest fire occurrence varies with types of drivers and their behavior. Amongst the natural drivers, climatic drivers such as temperature, humidity and precipitation have been reported to have strong correlation with forest fire occurrence (Abdi *et al.*, 2016; Bhujel *et al.*, 2017a; Charles & Steven, 2012; Chen *et al.*, 2014; Khanal, 2015; Knies *et al.*, 2010; Matin *et al.*, 2017; Mondal *et al.*, 2015; Pausas, 2004). In this connection, Abdi *et al.* (2016) have reported strong correlation between daily temperature and severity of forest fires in the Golestan, North-east Iran. Similarly, Charles and Steven (2012) have reported strong correlation between forest fire occurrence and precipitation in the South-eastern United States. Likewise, Chen *et al.* (2014) have assessed the relationship between precipitation and forest fire occurrence for the period of 1982-1988 and 1989-2008 in five eco-regions of Yunnan Province, China and reported that precipitation has significant negative correlation with the forest fire occurrence. Moreover, Pausas (2004) have revealed significant negative correlation between burnt area and summer precipitation in the Eastern Iberian Peninsula. Furthermore, Mondal *et al.* (2015) have observed the positive correlation between mean temperature and forest fire occurrence in India.

Likewise, in context of Nepal, Bhujel *et al*. (2017a), Khanal (2015) and Matin *et al*. (2017) have reported forest fire occurrence has strong positive correlation with temperature and negative correlation with precipitation and humidity.

Similarly, the topographic drivers are among the natural drivers causing forest fire (Dillon *et al*., 2011; Flatley *et al*., 2011; Fryer, 2016; Gralewicz *et al*., 2012; Guo *et al*., 2015; Holden *et al*., 2011; Kumar *et al*., 2015). For instance, Dillon *et al*. (2011) have reported that the topographic variables (aspect, elevation and slope) to be the strong predictors of fire occurrence in comparison to climatic variables (temperature and precipitation). Likewise, Flatley *et al*. (2011) have reported that forest fire occurrence is relatively high in the dry south-facing aspects, ridges and lower elevations in the Southern and Central Appalachian Mountains, USA. Similarly, Fryer (2016) has assessed correlation between forest fire occurrences and the topographic features (elevation and slope) and reported that forest fire frequency and severity increases with increase in slope and decrease in elevation. Likewise, Holden *et al*. (2011) have revealed that forest in the low elevation and south-facing aspects are highly fire vulnerable due to accumulation of more dry fuel and higher energy releasing components. In addition, Gralewicz *et al*. (2012) have reported that forest in the lower elevation and flatter areas are more prone to fire occurrence. Moreover, Guo *et al*. (2015) have reported that Boreal Forest of the lower elevations of China to be more susceptible to fire. Similar results have been observed in India (Kumar *et al*., 2015).

Forest fuel is another natural driver having significant positive correlation with forest fire occurrence (Bergeron *et al*., 2004; Johnson *et al*., 2001; Wu *et al*., 2014). According to Bergeron *et al*. (2004), forest fire occurrence is positively correlated with forest fuel in the Quebec's Southern Boreal Forest. Similarly, in the forest of Southern Rockies of Canada, Johnson *et al*. (2001) have reported that spatial composition of vegetation type and fire occurrence is positively correlated. Likewise, Wu *et al*. (2014) have revealed that forest fuel composition has strong positive correlation with forest fire occurrence in the North Eastern China.

Anthropogenic drivers like recreational activities and forest distance from settlement and road are the major drivers causing forest fire (Guo *et al*., 2015; Liu *et al*., 2012; Syphard *et al*., 2008). According to Guo *et al*. (2015) and Liu *et al*. (2012), in the Chinese Boreal Forest, forest fire occurrences are strongly correlated with human activities such as landscape accessibility-proximity to roads and settlements. Similarly, Syphard *et al*. (2008) have reported that forest fire occurrence is significantly positively correlated with anthropogenic activities like recreation (camping, hiking and hunting) and negatively correlated with forest distance from road and settlement.

In context of Nepal, various natural and anthropogenic drivers are playing important role in forest fire occurrence making forest more fire vulnerable. Among the natural drivers, climatic variables (temperature and precipitation) and forest fire occurrence have been reported to have strong correlation (Khanal, 2015; Matin *et al*., 2017; Parajuli *et al*., 2015). In this connection, Khanal (2015) has reported strong positive correlation between temperature and forest fire and negative correlation with precipitation. Likewise, Matin *et al*. (2017) have reported that Nepal's forest is at the high risk of fire due to temperature, forest fuel (vegetation) and topography (elevation and slope). Similarly, among the anthropogenic drivers, human-induced drivers have been reported to be strongly correlated with forest fire occurrence (Goldammer, 2003; Kanel, 2007; Karkee, 1991; Kunwar & Khaling, 2006; Matin *et al*., 2017). According to Goldammer (2003) and Kanel (2007), the forest fire has been increased due to human activities. Similarly, in the Tarai region of Nepal, Kunwar and Khaling (2006) have reported increase in forest fire due to human activities. Likewise, Karkee (1991) has observed that around 40% of forest fires in the Mid-hills of Nepal are caused by the human activities like cattle grazing, honey collection, poaching and non-timber forest product collection.

2.4 Forest biomass and carbon

In forest, biomass stocks vary according to forest types and geographical regions. Specifically, above-ground biomass stocks vary widely in the tropical forests due to regional differences in forest types, stem size distribution, soil fertility and topography as well as natural and human-induced disturbances (Borah *et al*., 2013; Devagiri *et al*., 2013; Hertel *et al*., 2009; Kumar *et al*., 2011). Borah *et al*. (2013) have estimated 32.5 to 261.6 Mg/ha above-ground tree biomass in the Tropical Forest of Assam, India. Similarly, Devagiri *et al*. (2013) have estimated around 70.0 t/ha and 33.0 t/ha biomass and carbon stock, respectively in the entire region of Karnataka, India. Likewise, Kumar *et al*. (2011) have observed 30.0 to 346.0 Mg/ha above-ground biomass stock in the forest of Northern Haryana and Siwalik region of the Western Himalayan, India.

Furthermore, Hertel *et al.* (2009) have reported that around 303.0 Mg/ha biomass and 128.0 Mg/ha carbon in the natural forest of Sulawesi, Indonesia.

The sapling, leaf-litter, herbs and grasses biomass vary in the different forest types (Odiwe & Muoghalu, 2003; Sanches *et al.*, 2008; Singh & Singh, 1991; Singh *et al.*, 2011; Zhou *et al.*, 2006). According to Odiwe and Muoghalu (2003), on average 9.9 to 12.5 t/ha/yr biomass have been reported from the secondary lowland rainforest of Nigeria. Similarly, Sanches *et al.* (2008) have estimated 8.0 to 10.5 t/ha/yr leaf-litter, herbs and grasses biomass in the Tropical Semi-deciduous Forest of the Southern Amazon Basin, Brazil. In China, approximately, 3.6 to 10.6 t/ha/yr litter biomass has been reported in the Sub-tropical Monsoon Evergreen Broad-leaved Forest (Zhou *et al.*, 2006). Likewise, Singh and Singh (1991) have observed that 13.97 t/ha/yr in shrub layer, 0.35 t/ha/yr in herbs layer and 2.83 t/ha/yr in the litter layer biomass in the forest of Northern Hariyana, India. Similarly, Singh *et al.* (2011) have reported that around 8.2 to 8.8 t/ha/yr litter-fall biomass in the rehabilitated Sub-tropical Forest in North India.

Regarding carbon stock, above-ground carbon stock varies according to forest types and geographical features (Chhabra *et al.*, 2002; FRA, 2011; Hertel *et al.*, 2009; Lu *et al.*, 2006; Mohanraj *et al.*, 2011; Pande & Patra, 2010; Saatchi *et al.*, 2011). According to FRA (2011), in 2010, globally, more than 650 billion tons of carbon have stored over four billion hectares forest. Among them, around 44% accounts in the main stem biomass, 11% in dead-wood and litter, and 45% in the soil. Similarly, Saatchi *et al.* (2011) have reported that around 247.0 Gigatonnes (Gt) carbon in the forest of three continents, namely Latin America, Africa and South-east Asia. Among them, 193.0 Gt carbon stored in above-ground and 54.0 Gt carbon stored in the below-ground biomass. Likewise, Hertel *et al.* (2009) have estimated 128.0 Mg/ha carbon in the natural forest of Sulawesi, Indonesia. In China, around 11.3 Tg (ranging from 8.5 Tg to 13.9 Tg) annual forest fire-induced carbon emission has been estimated from 1990 to 2000 (Lu *et al.*, 2006). Furthermore, in India, Chhabra *et al.* (2002) have estimated 135.6 t/ha carbon stock in the forests of Punjab, and Jammu and Kashmir. Similarly, around 4.5 Tg above-ground carbon stock has been estimated in the forest of Kolli hills (Mohanraj *et al.*, 2011). Likewise, 74.6-164.0 t/ha carbon has been estimated in the Haldwani forest of Deharadun (Pande & Patra, 2010).

In context of Nepal, biomass and carbon stock vary with different types of forest (Baral *et al*., 2010; DFRS, 2015). Baral *et al*. (2010) have reported that on average 217.5 t/ha above-ground biomass and 97.9 t/ha carbon stock in the Hill Sal Forest and 178.8 t/ha above-ground biomass and 80.5 t/ha carbon stock in the Tropical Riverine Forest of Nepal. Similarly, around 194.5 t/ha of above-ground air-dried biomass and 176.9 t/ha of carbon stocks have been reported in the forests of Nepal (DFRS, 2015).

2.5 Biomass available to burnt

The biomass available to burn found to varies based on the biomass avaiable in the different forest types. Kasischke *et al*. (2005) have been reported that, where the total above ground biomass is low (<10 t/ha), 80% of the biomass is available to burn; where above ground biomass is moderate (10-20 t/ha), 50% is available to burn; and where above ground biomass levels is high (>20 t/ha), only 35% biomass is available to burn.

2.6 Combustion efficiency

The fraction of biomass consumed during fire incidence (combustion efficiency) varies according to accumulation of forest fuel in the forest. Various authors have reported combustion efficiency of different types of forest. IPCC (1997) has reported 0.60% combustion efficiency for all types of normal forest in the Asian continent. Similarly, Venkataraman *et al*. (2006) have assessed the fraction of biomass consumed during fire and reported that on average 0.50% combustion efficiency for the dense forest of India. Likewise, Kasischke *et al*. (2005) have reported 0.075 t carbon/ha as combustion efficiency from surface fire.

2.7 Forest fire-induced carbon emission

The forest fire induced carbon emission varies according to characteristics of forest fuel, climatic and topographical conditions. The carbon emission differs at local, regional and global landscape levels. In context of carbon emission, various studies (Attiwill *et al*., 2013; Hoelzemann *et al*., 2004; Knorr *et al*., 2016; Pearson *et al*., 2017; Sibanda, 2011; Tedim *et al*., 2018; van der Werf *et al*., 2017) have reported increased in carbon emission due to forest fire in the recent years.

At global level, Attiwill *et al*. (2013) have reported three mega-fires in Victoria over the period from 2002 to 2009 causing adverse impacts on carbon emission, socio-economic and ecological aspects. Similarly, Hoelzemann *et al*. (2004) have assessed the Global Burnt Scar Satellite product (GLOBSCAR) based on MODIS data for the year 2000 and estimated 1741.0 Tg carbon, 5716.0 Tg CO_2, 271.0 Tg CO, 12.5 Tg CH_4 emission. Likewise, Pearson *et al.* (2017) have reported 17% carbon emission from forest fire in the Tropical and Sub-tropical Forest of 74 developing countries, during the period from 2005 to 2010. Moreover, Knorr *et al.* (2016) have reported likely increase in forest fire and carbon emission in the future due to climate warming, population growth and increase in productivity of forest fuel. Furthermore, Tedim *et al.* (2018) have reported impacts of extreme forest fire events on ecological and socio-economic aspects which is challenging and costly to control. In addition, van der Werf *et al.* (2017) have assessed the global forest fire incidences using burnt area dataset with small fires (Global Fire Emissions Database format (GFED3s and GFED4s) and carbon emission has been reported to be increased by 11% during the period between 1997 and 2011.

At regional level, various studies (Bowman *et al.*, 2017; Flannigan *et al.*, 2013; Kasischke & Bruhwiler, 2003; Street *et al.*, 2003; van der Werf *et al.*, 2006) have reported substantial increase in biomass burning and carbon emission causing adverse impacts on soci-economic and environmental sector. In this connection, Bowman *et al.* (2017) have reported disastrous socio-economic impacts of flammable-forest biomass in the sub-urban areas of the Western United States and South-eastern, Australia. Similarly, Flannigan *et al.* (2013) have shown increase in Cumulative Severity Rating (CSR) of forest fire by more than three times than the baseline CSR in the Northern Hemisphere by the end of the century. Likewise, Kasischke and Bruhwiler (2003) have reported 290.0-383.0 Tg of the total carbon, accounting 828.0-1103.0 Tg CO_2, 88.0-128.0 Tg CO and 2.9-4.7 Tg CH_4 emission from the Boreal Forest fire of five different regions of the North America and Russia, in 1998. In Asia, Street *et al.* (2003) have estimated 330.0 Tg biomass burn during the period from 1999 to 2000. Moreover, van der Werf *et al.* (2006) have reported that 49%, 13%, 11%, 9% and 6% carbon emission from the total global forest fire in Africa, South America, equatorial Asia and Australia, respectively during the period from 1997 to 2004.

In China, various previous studies (Lu *et al.*, 2006; Yin *et al.*, 2019; Zhang *et al.*, 2016) have reported varies quantity of carbon emission from forest fire. According to Lu *et al.* (2006), around 11.3 Tg carbon emission containing 40.6 Tg CO_2, 2.7 Tg CO and

0.11 Tg CH_4 from forest fires, during the period from 1950 to 2000. Similarly, Yin *et al.* (2019) have reported that on average 40.8 Tg/yr CO_2 emission from forest fire in China, in the period between 2003 and 2017. Likewise, Zhang *et al.* (2016) have reported 0.04 Tg to 7.2 Tg carbon emission during the period from 1988 to 2012. In India, Venkataraman *et al.* (2006) have reported burning of 32.0 Tg biomass per year from the dense forest during the period from 1995 to 2000. The similar study carried by Badarinath and Vadrevu (2011) reported annual 6.3 Tg of CO_2 emissions from forest biomass burning in India.

In context of Nepal, the global contribution of green house gas has been reported to be around 0.027% emissions, which is relatively insignificant (MoSTE, 2014). Similarly, Sibanda (2011) has revealed that on average 1669.0 Mg/ha carbon emissions from the forest of Ludikhola Watershed in Gorkha District. However, limited studies have been carried out to estimate the carbon emission in Nepal, especially on the high value lowland Tropical Mixed Broad-leaved Forest. Thus, this research has focused on the estimation of carbon emission due to forest fire.

2.8 Loss and damage of forest biomass and carbon

The loss and damage of forest biomass and carbon is increasing due to forest fire in the recent years (Beer *et al.*, 2010; Chang & Song, 2010; EEPSEA/WWF, 1998; IFFN, 2002; Keith *et al.*, 2014). At global level, loss and damage of biomass and carbon due to forest fire have been increasing in recent years (Beer *et al.*, 2010; Randerson *et al.*, 2012). According to Randerson *et al.* (2012), globally, 1.9 to 2.5 Pg carbon/year emission from 345.0 to 464.0 Mha/yr forest burning during the period from 2001 to 2010. Similarly, annually, around 123±8 Pg carbon has been reported to be lost due to burning of global terrestrial forest ecosystem (Beer *et al.*, 2010).

At regional level, according to Economy and Environment Programme for the South East Asia (EEPSEA/WWF, 1998) has reported forest resources damage equivalent to USD 4 billion from forest fire in the South-east Asia. Similarly, Chang and Song (2010) have reported 5.0 Tg/yr CO_2 loss due to the above-ground forest fires in Tropical Asia during the period from 2000 to 2006. Likewise, for the year 2009, Keith *et al.* (2014) have reported around 3.9 Tg carbon loss due to forest fire in the Temperate Forest landscapes in Australia.

In China, various preceding studies (Kunpeng & Yulong, 2016; Shu *et al*., 2001; Yi & Bao, 2016; Yin *et al*., 2019) have reported increase in loss of forest biomass in the recent years. According to Kunpeng and Yulong (2016), 46,096 km^2 forest area has been burnt in the Great Xing's Mountains (GXM) in between 1986 and 2010. Similarly, Shu *et al*. (2001) have reported around 0.68% annual forest damage. Likewise, Yin *et al*. (2019) have reported on average 40.8 Tg/yr CO_2 loss due to forest fire during the period of 2003-2017. Moreover, Yi and Bao (2016) have reported about 4-11% carbon loss due to forest fire in the shrub-land and grassland of Boreal Forest.

In India, the preceding studies (Badarinath & Vadrevu, 2011; IFFN, 2002; Satendra & Kaushik, 2014) have reported increase in loss of forest resources in the last decades. According to International Forest Fire News (IFFN) (2002), there is on average USD 107 million tangible monetary loss due to forest fire. Similarly, Badarinath and Vadrevu (2011) have estimated 6.3 Tg annual carbon loss due to forest biomass burning. Likewise, Satendra and Kaushik (2014) have reported over 3.7 million hectares of forests affected from forest fire resulting into annual loss of forest resources worth USD 104 million.

Nepal has been experiencing erratic forest fire events in the recent years which is in increasing trends causing degradation of forest ecosystems (Bajracharya, 2002; Bhujel *et al*., 2018b; DFRS, 2015; Goldammer, 2003; HMG/MoFSC, 2002; Kanel, 2007; Karkee, 1991; Khanal, 2015; Kunwar & Khaling, 2006; Matin *et al*., 2017; Parajuli *et al*., 2015; Sharma, 1996). According to Bajracharya (2002), 400,000 ha forest lost annually due to forest fire. Similarly, in Nepal, around 27.8% of forest fires affect the forest resulting in loss and damage to forest biomass (DFRS, 2015). Likewise, Goldammer (2003) has reported increase in forest fire due to human activities such as fire-wood collector, NTFP collector, wildlife predator, camp-fire and trash-fire. Nepal Biodiversity Strategy (2002) reported that forest fire as a serious threat to ecosystems and biodiversity in Nepal (HMG/MoFSC, 2002). Moreover, Kanel (2007) and Karkee (1991) have observed around 40% of forest fire in the Mid-hills is caused due to human activities like cattle grazing for new grass, honey collection, poaching and non-timber forest products collection. Likewise, Khanal (2015) has reported 375,000 ha forest damage due to forest fire during the period from 2001 to 2015. Kunwar and Khaling (2006) have reported increase in forest fire in the Tarai region of Nepal due to human activities. Moreover, Matin *et al.* (2017) have reported 18 districts of Nepal to be at the high risk of forest fires, where annually 12,269 forest fire incidences (occurrences) recorded from 2003 to 2013. In addition, they have also observed that forest nearby settlements and roads are more fire vulnerable and over 65% forest fire incidences in <1000 m elevation. Moreover, Parajuli *et al.* (2015) have reported 2159 annual forest fire incidences for the period from 2000 to 2013. Furthermore, Sharma (2006) has reported the community forests damage by 14% in 2003 and 24% in 2004 due to forest fire in Nepal. Similarly, in 2016, USD worth 1,07,798 forest resource was lost due to forest fire in Nepal (Bhujel *et al.*, 2018b).

2.9 Forest fire network and policies

In order to monitor and report forest fire incidences across the globe, Global Fire Monitoring Center (GFMC) has been established in 1998 as an advisory body of the United Nations (UN) that works in coordination with the UN International Strategy for Disaster Reduction (ISDR). It provides a global portal for forest fire documentation and information acquired from monitoring of fire events, which is open for the general public. The GFMC regularly updates national to global wildfire products and establish a world wide forest fire network as a coordinating and cooperating institution. According to Karns (2019), various regional level fire networks have been established which are functioning under the global fire networks. The regional networks include the Sub-saharan Africa, South Asia, South-east Asia, Australasia, North-east Asia, Central Asia, South America, North America, Meso-America, Caribbean, Eurasia, Mediterranean, South-east Europe and Euro-Alpine Sub-region. Nepal is one of the members of regional fire networks of the South Asia.

Nepal has formulated several policies, strategies and legal instruments relevant to the forest fire, which include Climate Change and UNFCCC Negotiation Process Report (2012). Forest Fire Management Strategy 2010 (GoN/MoFSC, 2010), National Adaptation Programme of Action to Climate Change 2010 (GoN/MoE, 2010), Scientific Forest Management Guideline 2014 (DoF, 2014), National Forest Policy 2019 (GoN/MoFE, 2019), Forestry Sector Strategy 2016-2025 (GoN/MoFE, 2019), Forest Act 2019 (GoN/MoFE, 2019),. The National Forest Policy (2019) has envisioned improving forest conditions through community participation for reducing forest degrading activities, including forest fire (GoN/MoFE, 2019). Forestry Sector Strategy

(2016-2025) has envisioned to develop tools and techniques for reducing forest fire incidences and damage caused by pests and diseases (GoN/MoFE, 2016). Likewise, Forest Fire Management Strategy (2010) has provisioned securing people's life, public properties and forest ecosystem through awareness and enhanced capacity with necessary tools and techniques at the local level (GoN/MoFSC, 2010). Forest Act (2019) has provisioned penalty up to NRs. 60,000 or imprisonment upto three years or both for the person committing forest fire (GoN/MoFE, 2019). Likewise, the National Adaptation Programme of Action to Climate Change (2010) has provisioned to improve the forest health and carbon sequestration by reducing forest fire (GoN/MoE, 2010). Similarly, Climate Change and UNFCCC Negotiation Process Report (2012) has reported the loss of forest resources including loss of species and wildlife habitat due to increase in drought-driven forest fire (GoN/MoEST, 2012). In addition, Scientific Forest Management Guideline (2014) has provisioned for construction of the fire line in every 200-400 ha forest compartment for sustainable forest fire management (DoF, 2014). However, the provision seems to be not followed in the study area. These policies and legal instruments help create an enabling environment for sustainable forest management. The forest fire occurrence is recurrent phenomena in Nepal causing substantial loss and damage of forest resources. The preceding works carried out in Nepal have mostly covered fire risk analysis and estimation of burnt areas. However, the identification of forest fire drivers, their contribution to fire occurrence, loss and damage of forest biomass and carbon emission, which are crucial for forest fire management seems missing, especially in the high value forest of the lowland of Nepal.

CHAPTER 3

3 MATERIALS AND METHODS

In order to achieve the objectives of the present study, various materials and methods have been used for data collection and analysis. In this section, study area description, methods applied for data collection and analysis have been described.

3.1 Description of study area

3.1.1 Study area

Nawalparasi district, in the present federal structure, is located under the Gandaki Province in the geographical coordinates between 27°21'-27°47' North latitude and 83°36'-84°35' East longitude covering an area of 2,162 km^2, i.e., 1.5% of the total area of country (Fig. 2).

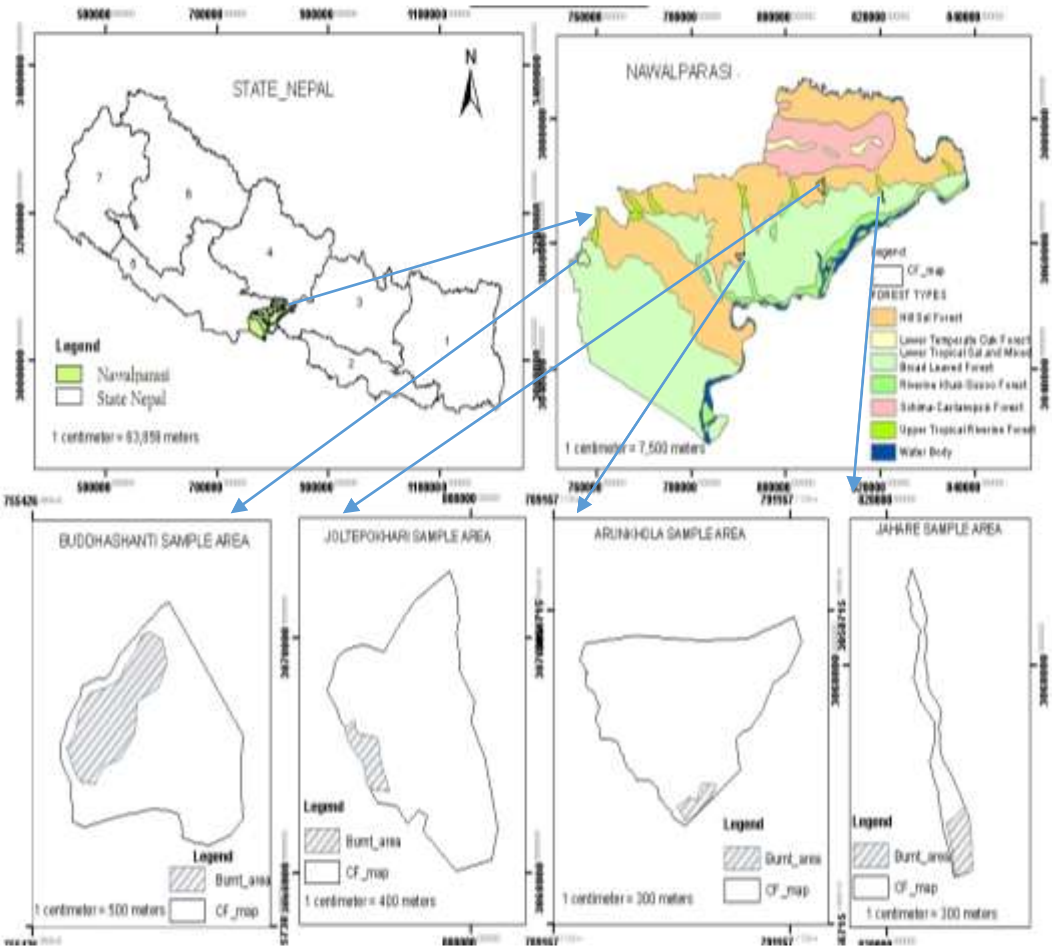

Figure 2: Location of study area and different community forests (Data source: DoFS, 2002)

The district is situated in the mid part of the east-west length of the country and is famous due to its historical importance as it encompasses "Ramgram" the maternal home place of the Buddha. The district is surrounded by Rupandehi District on west, Palpa and Tanahun Districts on north, Chitwan District on east and south, and the Indian border to the south. The longest stretch (99 km) of the national highway passes through this district. The present study has considered four community forests of Nawalparasi district, *viz*. Budhasnti Community Forest, Arunkhola Community Forest, Jholtepokhari Community Forest and Jhahare Community Forest as the representative of the Tropical Mixed Broad Leaf Forest of Nepal.

Budhasanti Community Forest

The Budhasnti Community Forest is natural and dense forest which constitutes around 60-80% crown cover. It is located in the geographical coordinates between 27°37'54.54"-27°36'31.53" North latitude and 83°37'05.71"-83°35'38.12" East longitude with altitude ranging from 112 to134 m covering an area of 430.13 ha in the Tarai region (Fig. 2).

Arunkhola Community Forest

The Arunkhola Community Forest is natural and dense forest. It is located in the geographical coordinates between 27°37'23.83"-27°36'35.76" North latitude and 83°57'09.34"-83°55'58.50" East longitude with altitude ranging from 179 to 195 m covering an area of 137.34 ha (Fig. 2).

Jholtepokhari Community Forest

The Joltepokhari Community Forest is one of the dense natural forest. It is located in the geographical coordinates between 27°42'05.55"-27°43'25.65" North latitude and 84°07'33.23"-84°06'26.17" East longitude with altitude ranging from 424 to 538 m covering an area of 264.42 ha (Fig. 2).

Jhahare Community Forest

The Jhahare Community Forest is the one of the plantation riverine forest. It is located in the the geographical coordinates between 27°42'13.64"-27°41'07.94" North latitude and 84°15'07.34"-84°14'47.08" East longitude with altitude ranging from 198 to 260 m covering an area of 23.76 ha (Fig. 2).

3.1.2 Climate

Climatically, the district exhibits varied climatic condition ranging from tropical, subtropical to lower temperate. The average maximum monthly temperatures varies from 24.39±0.42°C in January to 37.78±0.35°C in May, and minimum temperature from 8.25±0.39°C in January to 25.74±0.15°C in August, with defined rainy season from June to September. In active fire season (March-May), average maximum temperature varies from 31.20°C to 37.78°C and minimum temperature 14.60°C to 23.47°C. Similarly, the area revealed the maximum mean annual precipitation 797.41±75.74 mm during July through May with minimum 19.46±5.71 mm precipitation during pre-monsoon, i.e., February to May, and negligible precipitation during post-monsoon period, i.e., October through January. The humidity varied from minimum 58.12±2.89% in April to maximum 89.61±.42% in December (Table 1) (DHM, 2017).

Table 1: Climatic condition of the study area during study period (2000-2017. Units: temperature in °C, humidity % and precipitation in mm

Season		Max. Temp	Min. Temp	Humidity	Precipitation
Post-monsoon	Oct	34.05±0.30	21.51±0.34	86.45±0.76	63.65±18.53
	Nov	30.05±0.30	14.01±0.43	88.73±0.55	10.07±4.29
	Dec	24.66±0.51	10.83±0.20	89.61±0.42	0.32±.213
	Jan	24.39±0.42	8.25±0.39	87.08±0.50	14.20±4.44
Pre-monsoon	Feb	27.46±0.47	11.27±0.35	78.74±1.00	29.07±10.87
	Mar	31.20±0.33	14.60±0.72	61.45±2.12	19.46±5.71
	Apr	36.93± 0.29	21.55±0.40	58.12±2.89	71.90±14.20
	May	37.78±0.35	23.47±0.19	65.56±1.75	220.35±36.42
Monsoon	Jun	37.67±0.20	25.38±0.23	75.91±1.13	481.79±40.35
	July	35.39±0.26	25.58±0 .12	83.52±0.51	797.41±75.74
	Aug	34.22±0.32	25.74±0.15	84.61±0.36	647.60±68.08
	Sept	35.25±0.18	25.11±0.12	85.17±0.58	279.41±42.97

3.1.3 Physiography

Physiographically, the district constitutes Terai, Siwalik and mountain having elevation range from 91 m to 1916 m above the mean sea level (Fig. 3). Terai region has a flat and fertile land covered with dense tropical to sub-tropical forests. The Siwalik region is a narrow belt of fragile and rugged mountain having 15-20 km width extending east-west and the slope range from 15° to 45°. The mountain are characterized with steep slopes and nearly uninhabited. Topographically, by slope, 58.9% area of the district falls within 15%, 21.8% area between 15 to 30%, and 19.2% area at >30% (Fig. 3). By aspect, east, south, north and west composed of 28.4%, 27.0%, 22.2% and 19.7% area, respectively (Table 2). With respect to elevation, in the elevation, gteater area of the district falls within (15,82,117.1 ha) <500 m compared to >1000 m elevation (4,46,113.8 ha) and least area (12,764.3 ha) occupied in the elevation range 500-1000 m. In the >1000 m elevation, the upto1300 m elevation has considered for study due to distribution of Hill Sal Forest up to this elevation.

Table 2: Area coverage with aspects slope and elevation in the Nawalparasi district

Topographic features		Total area (ha)	Area (%)
Aspects	East	61315.5	28.4
	West	42519.2	19.7
	North	47874.9	22.3
	South	58210.6	27.0
	Flat area	5675.1	2.6
Total		215595.3	100
Slopes (%)	< 15%	127166.9	59.0
	15-30%	47064.5	21.8
	>30%	41363.9	19.2
Total		215595.3	100
Elevation (m)	<500	158217.2	73.4
	500-1000	12764.3	5.9
	>1000	44613.8	20.7
Total		215595.3	100

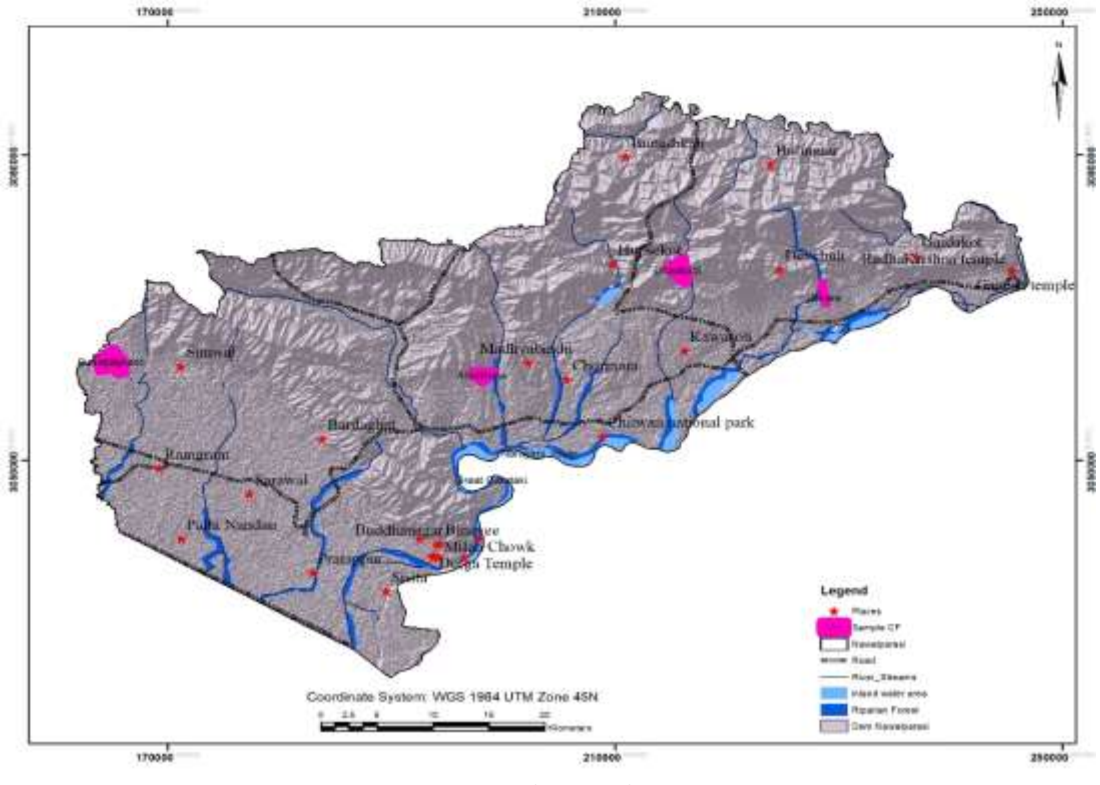

Figure 3: Topographic feature of Nawalparasi district

3.1.4 Forest types

In Nepal, 35 types of forest have been reported (DoF, 2002). Among the forest types, in Nawalparasi district, five types of forest, *viz*. Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF), Hill Sal Forest (HSF), Riverine Forest (RF), Schima-Castanopsis Forest (SCF) and Chir-pine Broad-leaved Forest (CBF) are found (Fig. 4). The Lower Tropical Sal Mixed Broad-leaved Forest is distributed from 83 to 600 m altitude. The *Shorea robusta* is the dominant tree species with associated species *Terminalia alata, Lagerstroemia parviflora, Syzygium cumini, Anogeissus latifolia and Buchanania latifolia*. This forest constitutes around 60-80% crown cover. Most of the trees are matured with high biomass. The Riverine Forest also occurs in the similar location, where *Dalbergia sissoo* and *Acacia catechu* are the main tree species. Likewise, Hill Sal Forest is also dominated by *Shorea robusta* with having *Terminalia alata, Terminalia bellarica, Lagerstroemia parviflora, Anogeissus latifolius* and *Syzygium cumini* as the associated species distributed from 300 to 1300 m altitude from sea level. In the Schima-Castanopsis Forest, *Schima wallichii* and *Castanopsis indica* are the major species.The Chir-pine Broad-leaved Forest (CBF) includes *Pinus roxburghii* and *Quercus* spp. The present study has concentrated in the Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF), Hill Sal Forest (HSF) and Riverine Forest (RF). The Hill Sal Forest, Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest, respectively covering 54,808.2 ha, 40,781.2 ha and 260.0 ha area including shrub and grass land (Table 3, Appendix I).

Table 3: Forest types of study area

Forest types	Area (ha)
Lower Tropical Sal-mixed Broad-leaved Forest	40,781.2
Hill Sal Forest	54,808.2
Riverine Forest	260.0
Total	95849.4

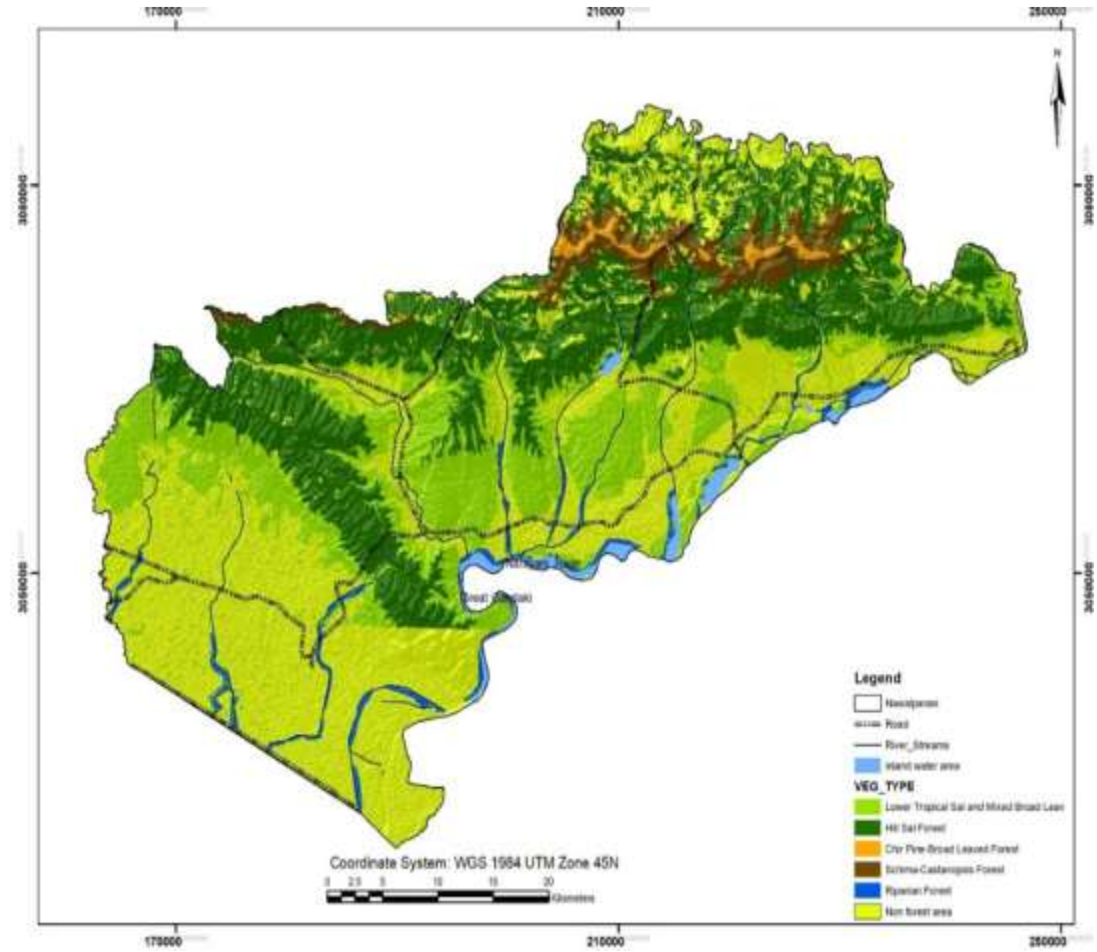

Figure 4: Forest types of Nawalparasi district

3.1.5 Demography

With respect to demography, the district constitutes 128,793 households and 643,508 populations with average household size 5 the sex ratio 89.4 and population density 298 km^{-2}, and the total male population is 30,3675 and the female is 3,39,833 (CBS, 2011).

3.1.6 Access of road networks

Nawalparasi is one of the accessible districts of Gandaki Province in terms of road network, including east-west national high-way, district roads, urban and village roads. In terms of roads network, the district constitutes 1853.49 km accessible roads including 1,060.29 km village road and 1,234.17 km all weather roads GoN/MoFALD (2016). The road density of the district accounts to be 18.53 km per 100 km^2 area and influencing population 347 per km against the national road density 9.14 km per 100 km^2 area and influencing population 1980 per km road (GoN/MoFALD, 2016).

3.1.7 Land use

In Nawalparasi district, the main land use are forest, shrub, grassland, agriculture, settlement, wetland and other types. Out of the total area of the district, 1,04,693 ha (48.6%) including 5-10% tree cover is covered by forest, and shrub 713 ha (0.33%) land, respectively. Similarly, 1,09,849.0 (51.03%) area is occupied by cultivated land and settlement, respectively (Table 4).

Table 4: Land use pattern in Nawalparasi district

SN	Land use	Area (ha)	Percentage (%)
1.	Forest (5-10% tree cover)	1,04,693.0	48.64
2.	Shrub	713.0	0.33
3.	Cultivated land and settlement	1,09,849.0	51.03
	Total	2,15,255.0	100.0

Source: DFRS, 2015

3.2 Methods

In order to achieve the objective of the present study, the methodological framework has presented in the Fig. 5. The methodological framework includes the process of identifying the fire drivers, their contribution to the forest fire occurrence and estimation of the biomass loss and carbon emission. The forest fire driver identification, prioritization and verification were carried out by public perception through participatory approach. Information regarding forest fires were obtained from MODIS active fire data and topographic map, and road and settlement data were obtained from the Survey Department, Government of Nepal. Similarly, forest type data were acquired from the Department of Forests and Soil Conservation, Government of Nepal and climatic (temperature, humiity, precipitation) data were collected from the Department of Hydrology and Meteorology, Government of Nepal.

The total above ground biomass of the unburnt and burnt forest was estimated according to Chave *et al.* (2005) and Tamarkar (2000). The biomass fraction consumed during the forest fire was estimated by calculating biomass difference between the non-burnt and burnt forests. The carbon stock was estimated by using 0.47 fraction value (IPCC, 2006). The loss and damage of biomass were estimated by the stock difference method (IPCC, 2006). The carbon emission due to forest fire was estimated by using Kasischke *et al.* (2005) (Fig. 5).

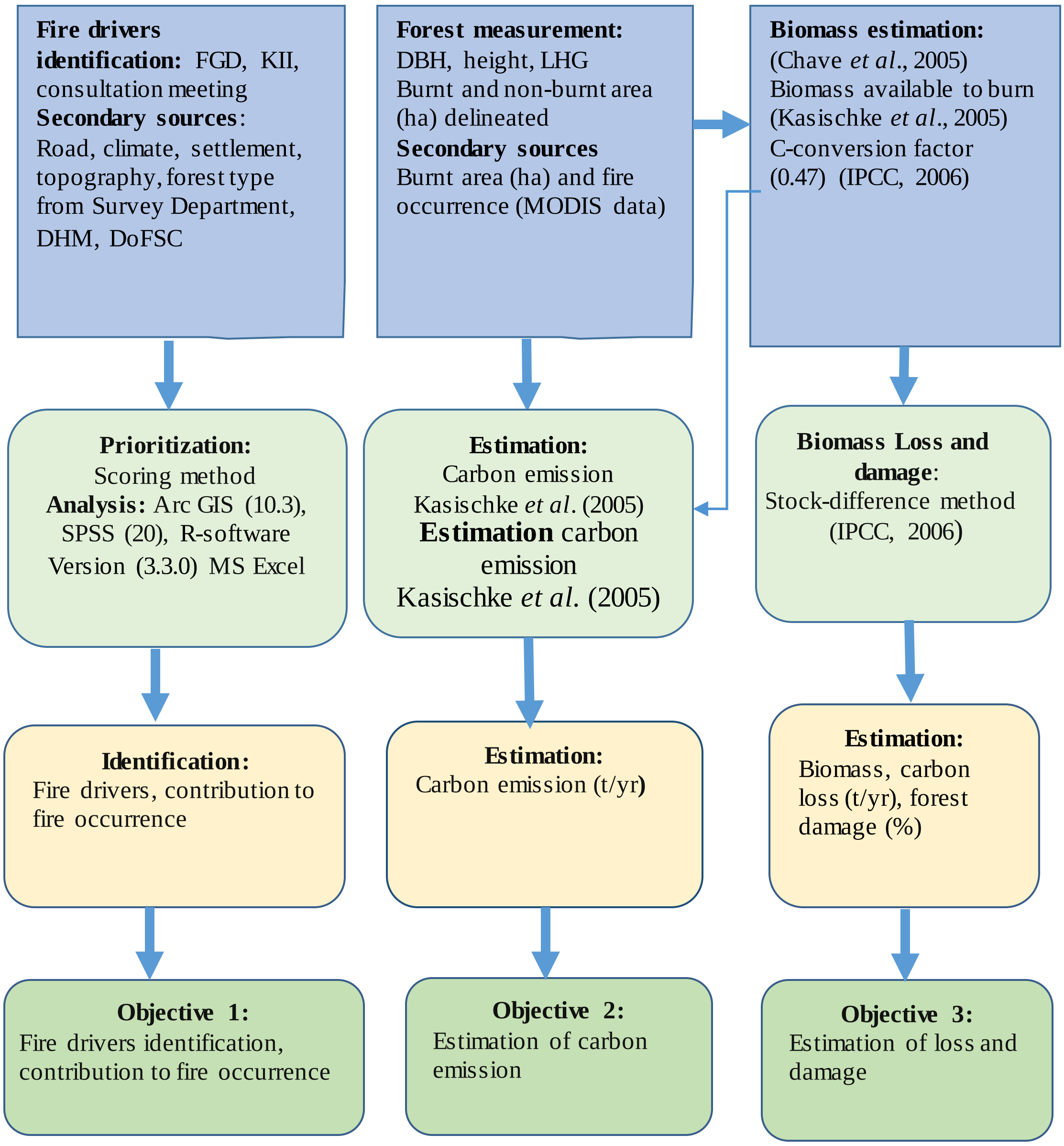

Figure 5: Methodological framework

3.2.1 Sampling design

In order to determine the sampling area, different strata of the Lower Tropical Sal Mixed Broad-leaved Forest, Hill Sal Forest and Riverine Forest were prepared using ArcGIS software (10.3 version) from digital forest types map of Nepal (DoF, 2002) (Fig. 6). Then the stratification was done on the map. From these forest strata, four community managed forests (Budhasanti, Arunkhola, Dhaubadi and Jhahare) were selected purposively on the basis of forest fire vulnerability and topographic representation. The forest fire vulnerability information was derived from the District Forest Five Years Management Plan (DFO, 2013) of Nawalparasi and topographical related information was received from the Digital Elevation Map (DEM) of the

Survey Department, Government of Nepal (2014). In each sampling forest, the non-burnt and burnt area was delineated with the help of GPS. The plants present in the community forests were divided into the major three groups, i.e., tree, pole (DBH >5 cm), sapling (DBH 1-5 cm) and leaf-litter, herbs, grasses and regeneration. Each stratum was considered as a block and samples were distributed proportionately with the help of fishnet software.

3.2.2 Sampling process

In order to carry out the sampling in the community forests, pilot sampling was carried out to calculate the number of sample plots based on the optimum allocation method. For this purpose, 10 samples were randomly selected from each stratum, then biomass was estimated to determine the required number of sample plots. Following formula was applied to determine the number of sampling plots in the forest.

$N = (CV^* t/E)^2$ *(Eq. 1)*

Where,

N	Number of sample plots
CV	Coefficient of variation of biomass CV =S/x
S	Standard deviation $S = \sqrt{\sum(\mathrm{x}-\bar{\mathrm{x}})^2/(\mathrm{n}-1)}$
X	Biomass of trees
t	Student's t-distribution table at n-1 degree of freedom (df) at 10% probability but in (n-1)
n	Number of sample plots taken as pilot sample that is 10-15
E	Sampling error at 10% $\mathrm{E} = \frac{S}{\sqrt{n}}$
S	Standard deviation

Altogether, 92 sample plots were laid down in the four purposively selected forests (Table 3). Sample plots were allocated at the intervals of 250 m on the burnt and non-burnt forest using the fishnet program (Table 5, Figs. 7-10). The coordinate of each sample plot was downloaded in the GPS receiver and laid out in the sampling forest for biomass estimation.

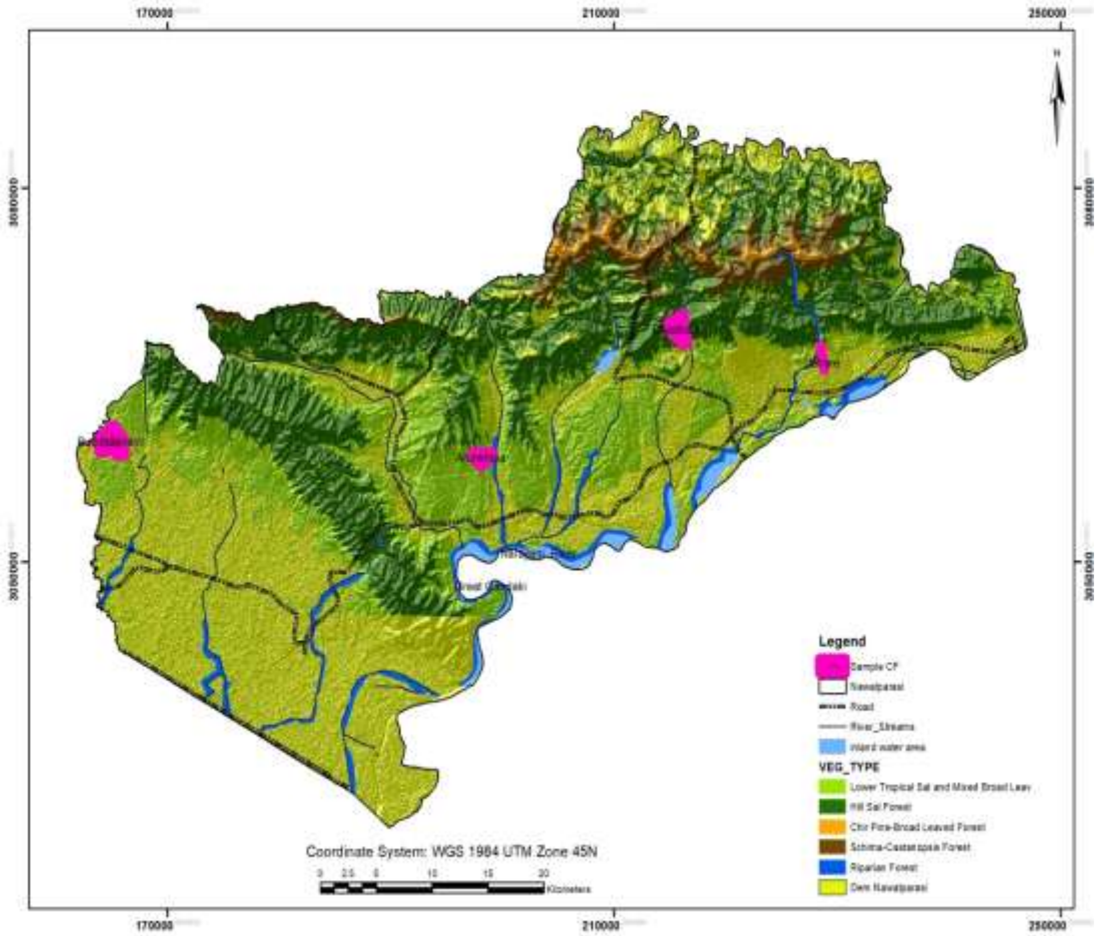

Figure 6: Study area showing Forest types and sampling community forest

Table 5: Distribution of sample plots in the different forests

Name of forest	Forest types (strata)	Sampled area (ha)		Allocation of plots	
		Total	**Burnt**	**Non-burnt**	**Burnt**
Budhasanti Community Forest	Lower Tropical Sal Mixed Broad-leaved Forest	430.13	98.9	33	10
Arunkhola Community Forest	Hill Sal Forest	137.34	3.22	13	3
Jholtepokhari Community Forest	Hill Sal Forest	264.42	13.30	25	3
Jhahare Community Forest	Riverine Forest	23.76	6.55	3	2
Total		855.67	121.97	74	18

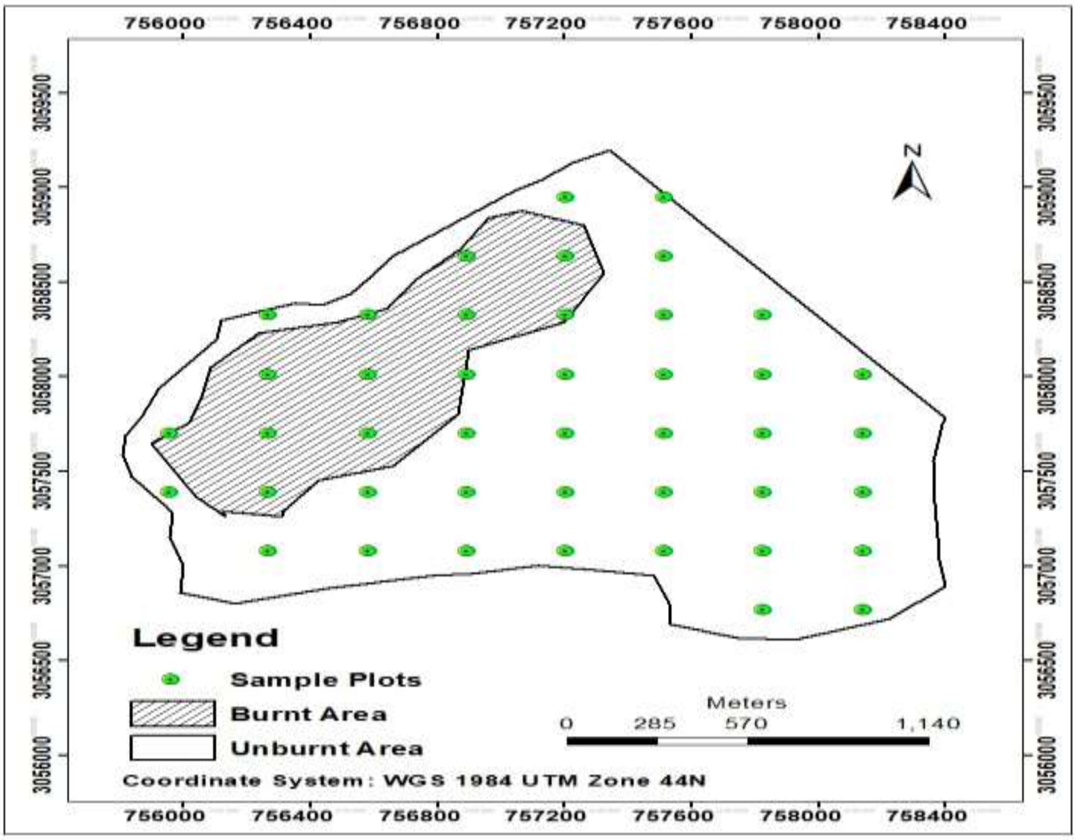

Figure 7: Distribution of sampling plots in Budhasanti Community Forest

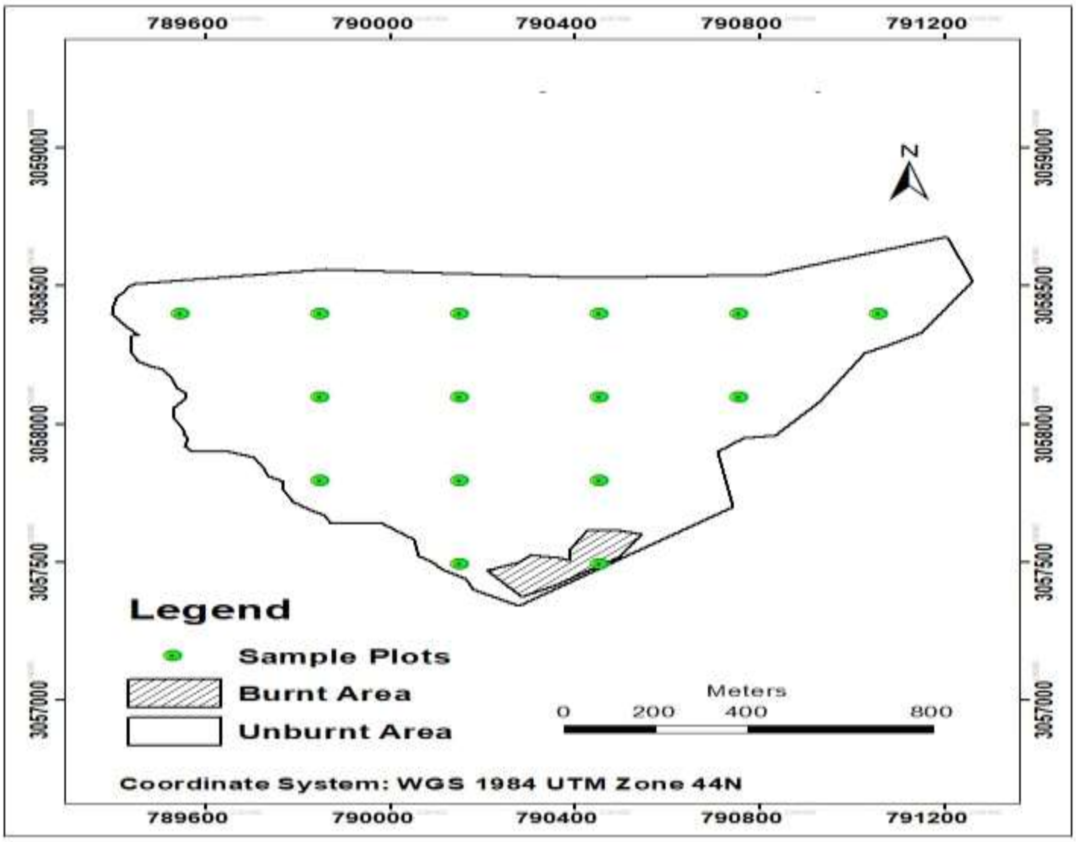

Figure 8: Distribution of sampling plots in Arunkhola Community Forest

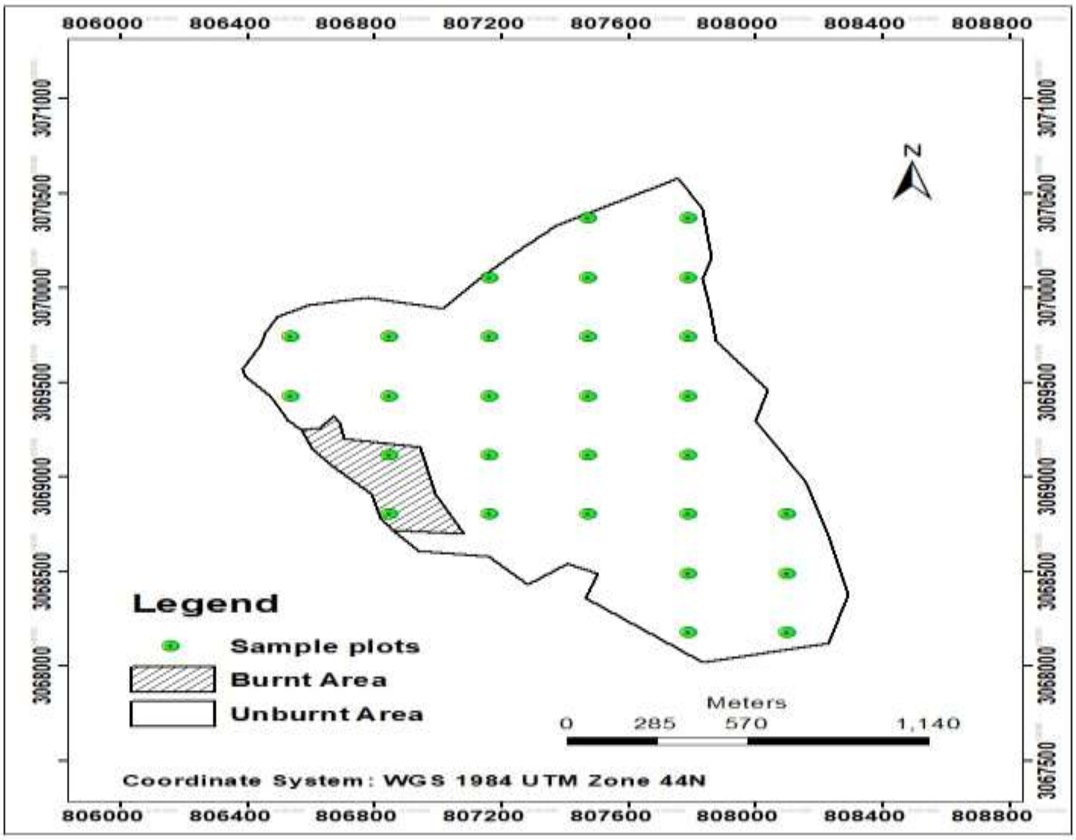

Figure 9: Distribution sampling plots in Jholtepokhari Community Forest

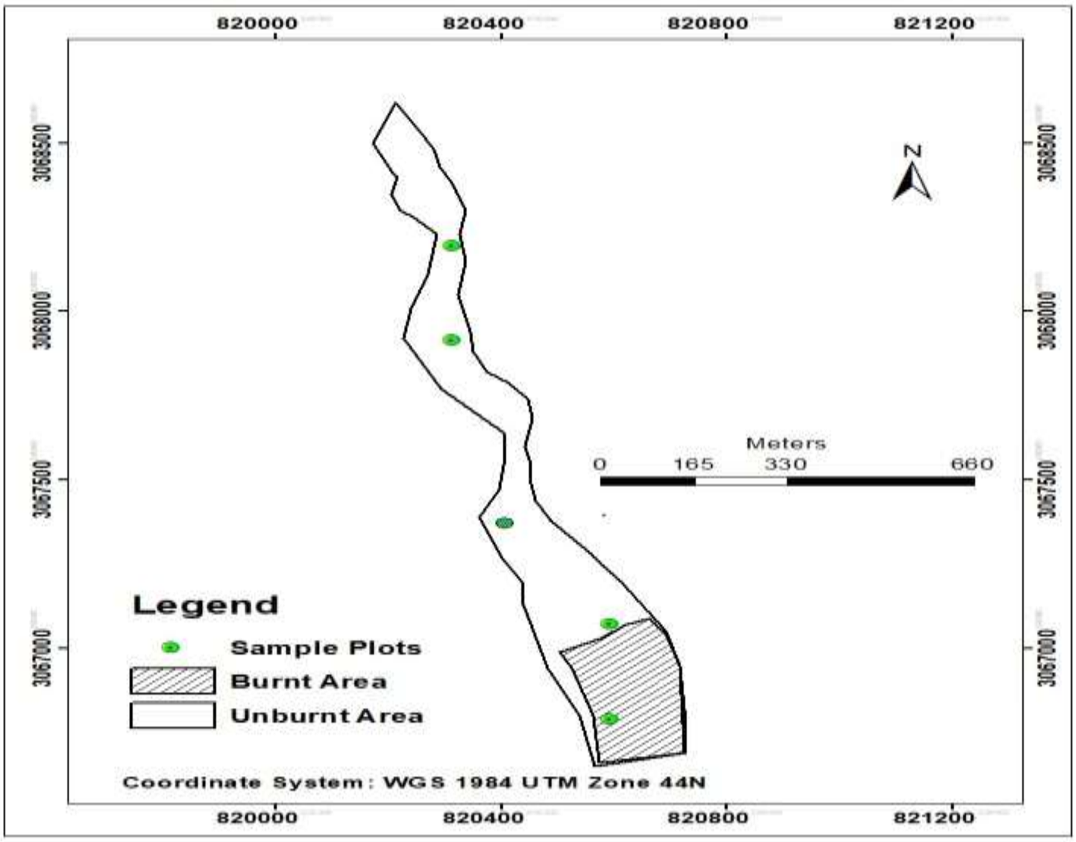

Figure 10: Distribution sampling plots in Jhahare Community Forest

With respect to sample plots establishment, the nested fixed plots were established by navigating the coordinate in the field.

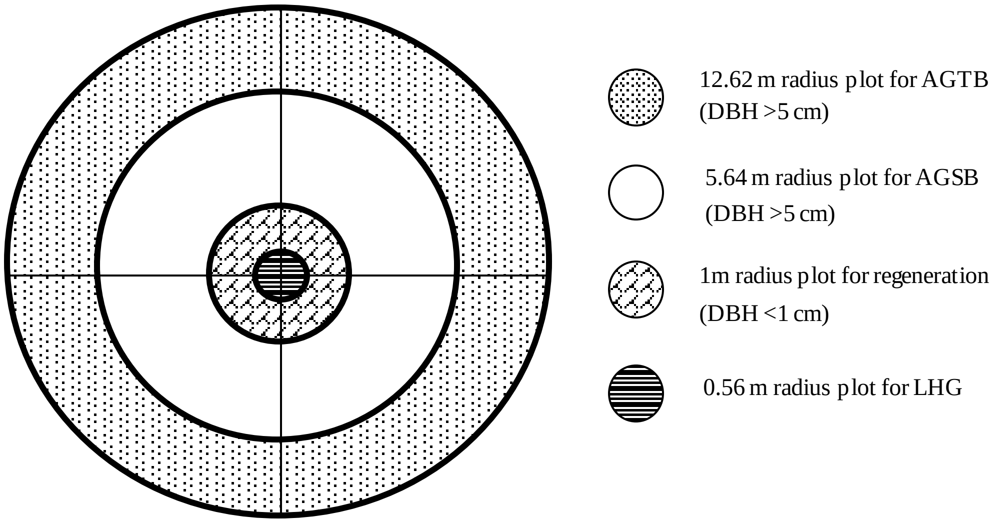

Figure 11: Nested circular plot used for sampling vegetation

For tree stratum (DBH >5 cm), circular plots having 12.62 m radius, for sapling (DBH 1-5 cm), nested circular plots having 5.64 m radius, for regeneration, nested plots with 1 m radius and for leaf litter, herbs and grasses (LHG), nested plots having 0.56 m radius were established (Fig. 11) (DoF, 2003).

3.3 Data collection and analysis

In order to achieve the purpose of the present study, the forest fire occurrence, burnt area, fire drivers and their contribution to forest fire occurrence, estimation of biomass loss and carbon emission related information were collected by using following methods.

3.3.1 Forest fire occurrence and burnt area

The forest fire occurrences (incidences) and burnt areas from 2001 to 2017 were estimated from the MODIS active fire data obtained from the National Aeronautics and Space Administration (NASA). The coordinates of the forest fire points and the date of occurrences were downloaded from https://firms.modaps.eosdis.nasa.gov/ download/ in the form of shape-files.

The forest burnt area due to fire was estimated using the burnt-area product (MCD45A1 collection 5.1), a monthly 500 m spatial resolution gridded burnt-area product downloaded from the server (ftp://ba1.geog.umd.edu/Collection5/TIFF/ Win18/). The product is based on bi-directional reflectance model-based change detection approach for mapping burnt-areas. The algorithm used in MODIS detects the approximate date of burn based on the observed changes in the daily MODIS reflectance product. The shape-file of the forest types of Nepal was obtained from the Department of Forests, Government of Nepal (DoF, 2002). From the shape-file, burnt area was delineated using the Arc-GIS (10.3 version) by clipping the boundary of the study area. The burnt area data from the database file (dbf) was converted to excel file to estimate burnt area. The accuracy of the burnt area was validated by direct field observation and also comparing with the general accuracy statement of the MOD14 product performance.

3.3.2 Forest fire drivers

With respect to identification of forest fire drivers, all the possible drivers were listed through participatory approaches like Focus Group Discussion (FGD), Key Informant Interview (KII) and Consultation Meetings with multi-stakeholders and observation. In this connection, five FGDs were conducted with four community forest user groups and one forest fire watcher group with 8-10 participants. Altogether, total 39 individuals participated during the discussion, which were guided by the checklist (Figs. 12, 13, Appendices I, II).

With respect to the prioritization of fire drivers, the major fire drivers were prioritized by the scoring method through people's perception. For scoring, two criteria were developed based on the magnitude of fire frequency and severity of fire. With respect to frequency, 0 denotes no fire occurrence in that year, 1 denotes one incidence of fire in the year, 2 denotes two incidences of fire and 3 denotes three or more incidences of fire within the year. Similarly, with respect to severity, 0 denotes no severe fire occurrence in the year, 1 denotes burning of only ground vegetation (Leaf litter, Herbs and Grasses), 2 denotes forest burning up to two meter height and 3 denotes burning of forest more than two meter height. These scores of fire drivers were compiled and converted into percent in order to prioritize the fire drivers. Based on the score, fire drivers were ranked and top scored drivers were selected as the major drivers for further analysis.

Figure 12: Consultation meeting with Division Forest Office

Figure 13: Focus group discussion with Joltepokhari forest user group

Similarly, five Consultation Meetings were carried out with the Department of Forests and Soil Conservation (DoFSC), Division Forest Office (DFO), Nawalparasi, Sub-division Forest Office, Nawalparasi, Nepal Forester's Association, Nawalparasi (District) Chapter of Federation of Community Forestry Users Nepal (FECOFUN).

The Consultation Meetings aimed verifying the identified fire drivers and obtaining information about the forest fire history, potential causes of forest fire and their possible solution following the checklist (Appendix II). Moreover, Key Informant Interviews (KIIs) were conducted with 10 informants from the Department of Forests and Soil Conservation, Divisional Forest Office, leader of the community forests, local civil society organizations, the local leaders of FECOFUN district chapter and forest fire watcher group (Appendix III). In the KIIs, the identified forest fire drivers were verified and information related to forest fire history, potential drivers of forest fire and possible solutions to reduce forest fire were collected.

Natural drivers

Regarding climatic driver, the temperature, humidity and precipitation data from 2000 to 2017 were collected from the Department of Hydrology and Meteorology, Government of Nepal. The maximum and minimum temperature and precipitation data were arranged by month, season and year.

With respect to topographic driver (aspect, slope and elevation), tiff file data were obtained from the Survey Department, Government of Nepal (2014). The topographic factors were further analyzed using the Digital Elevation Model (DEM) of Nepal. The DEM shape-file of Nepal was clipped by aspect, slope and elevation of Nawalparasi district. The shape-file layer of aspect, slope and elevation were produced separately. The digital maps of aspect, slope and elevation were prepared separately and each map was re-classified by using the spatial join analysis tool of the ArcGIS process. Moreover, the aspect map was re-classified into north, south, east and west for further analysis. Similarly, the slope map was also re-classified into three groups, i.e., slope <15%, 15-30% and >30% by using ArcGIS function for further forest fire analysis. Likewise, the elevation map was re-classified into three groups based on their elevation gradient, i.e., elevation <500 m, 500-1000 m and upto 1300 m for further analysis of forest fire.

For estimating forest fuel (biomass) driver, the forests were stratified into three strata based on the forest types: Lower Tropical Sal Mixed Broad-leaved Forest, Hill Sal Forest and Riverine Forest. From these forest strata, four community-managed forests namely Budhasanti, Arunkhola, Joltepokhari and Jhahare were selected purposively based on fire vulnerability and topographic representation. The vegetation present in the each community forest were divided into the three major groups, i.e., tree (DBH >5 cm), sapling (DBH 1-5 cm) and leaf-litter, herbs, grasses. Each stratum was considered as a block and the sampling plots were allocated proportionately with the help of fish-net software in each block. The number of the sampling plots was determined based on the optimum allocation method (coefficient of variables) for the community forests maintaining 1% sample intensity. In total, 92 sampling plots were designed for the estimation of biomass as forest fuel. In each the sample plot, a circular plots having 12.56 m radius for (DBH >5 cm) for tree, 5.64 m radius nested plots for sapling, and 0.56 m radius nested plots for Leaf-litter, Herbs and Grasses (LHG) were established. The height and diameter at breast height (DBH) of tree and sapling were measured with the help of clinometer and diameter tape, respectively (Appendices IV, V). Similarly, the LHG were destructively collected from the field and brought to the laboratory for estimating forest fuel and biomass.

Above ground tree biomass

The Above Ground Tree Biomass (AGTB) was estimatated according to Chave *et al.* (2005).

$$AGTB = 0.0509\ p\ D^2\ H \qquad (Eq.\ 2)$$

Where,

AGTB	Above ground tree biomass (kg)
P	Wood specific gravity (g cm^{-3})
D	Tree diameter at breast height (cm)
H	Tree height (m)

In this equation, D (cm) and H (m) values were obtained from the field, *p,* i.e., the species-wise wood specific gravity (g cm^{-3}) value was used from DFRS (2015) and Sharma and Pukkala (1990) (Appendix VI).

Above ground sapling biomass

The Above Ground Sapling (DBH 1-5 cm) Biomass (AGSB) was estimated by using the regression model (Tamrakar, 2000). The biomass values of saplings include foliage, branch and stem compartments. The following equation was used to calculate biomass (Appendix VII).

$$Log\ (AGSB) = a + b\ log\ (D) \qquad (Eq.\ 3)$$

Where,

Log	Natural log (dimensionless)
AGSB	Above-ground sapling biomass (kg)
a	Intercept of allometric relationship for saplings (dimensionless)
b	Slope of allometric relationship for saplings (dimensionless)
D	Over bark DBH (cm)

The D (cm) over bark value was obtained from the field measurement within the 5.64 m radius circular plots. Species wise ‘a’ and ‘b’ values were used from national allometric biomass tables (Tamrakar 2000) (Appendix VII).

Above ground leaf-litter, herbs and grasses biomass

The above ground Leaf-litter, Herbs and Grasses (LHG) biomass was determined by field samples collected destructively within 0.56 m radius. The fresh samples were weighed in field and were well-mixed, and then sub-samples were placed in a marked plastic zip bag. The sub-samples were brought to the laboratory of the Central Department of Environmental Science, Tribhuvan University, Kathmandu and oven dried at 105°C until the constant weight.

The per unit area biomass of leaf-litter, herbs and grasses was estimated using the following equation;

$$LHG = \frac{\text{Wfield}}{\text{A}} \times \frac{\text{Wsubsample dry}}{\text{Wsubsample wet}} \times \frac{1}{1000} \qquad \textit{(Eq. 4)}$$

Where,

LHG	Biomass of leaf litter, herbs, and grass (t/ha)
W_{field}	Weight of the wet LHG within an area A
A	Size of the area (ha)
$W_{sub\text{-}sample,\ dry}$	Weight of the oven-dried sub sample LHG (g)
$W_{sub\text{-}sample\ wet}$	Weight of the wet LHG (g) taken to laboratory

The moisture content is presented in the Appendix VIII.

The Total Above Ground Biomass (TAGB) was calculated by summing-up the total Above Ground Tree Biomass (AGTB), Above Ground Sapling Biomass (AGSB) and leaf-litter, herbs and grasses (LHG) as shown in the equation 5.

$$TAGB = AGTB + AGSB + LHG \qquad \textit{(Eq. 5)}$$

Total biomass was used for forest fuel and biomass to estimate carbon emission and loss.

Anthropogenic drivers

The anthropogenic driver, i.e., road networks and settlements were obtained from the Survey Department, Government of Nepal. The forest distance from roads and settlement were re-defined and buffered at the distances intervals of 500 m, 500-1,000 m and >1,000 m using the multi-ring buffer tool from ArcGIS software (10.3 version). These re-classified shape-files of each settlement and road were used for analyzing forest fire occurrence in each defined distance intervals. The forest fire incidences and burnt area were calculated by each fire drivers using ArcGIS.

3.3.3 Estimation of biomass and carbon

The total above ground biomass was estimated using the equations 1-4 developed by Chave *et al.* (2005) and Tamarkar (2000). Similarly, the total forest carbon stock was estimated by multiplying the total above ground biomass with default carbon fraction of 0.47 (IPCC, 2006).

3.3.4 Biomass available to burn

The fraction of the above ground biomass available to burn was estimated by using Kasischke *et al.* (2005). According to them, the area where total Above Ground Biomass (AGB) is low (<10 t/ha), 80% of the above ground biomass is available to burn, where there are moderate levels of above ground biomass (10-20 t/ha), 50% of the AGB is available to burn and where there are high above ground biomass levels (>20 t/ha), only 35% biomass is available to burn. The present study area shows >20 t/ha biomass accounting 35% of biomass available to burn. Thus, this value (35%) was adopted for the present study as the biomass available to burn. This method of estimation of biomass available to burns was used in various preceding studies (Dwomoh, 2009; Sibanda, 2011). Dwomoh (2009) has applied this method to estimate the biomass available to burn for the quantification of fire induced carbon emission in the Afram Headwaters Forest Reserve of tropical forest in Ghana. Similarly, In Nepal, Sibanda (2011) has applied this method to estimate biomass available to burn for estimating the fire induced carbon emission in the tropical forest of Ludikhola Watershed of Gorkha District.

3.3.5 Combustion efficiency

In the present study, the combustion efficiency was determined by dividing the consumed fuel (biomass), during combustion process, by the forest fuel available to burn.

3.3.6 Estimation of carbon emission

The fire-induced carbon emission from the forest of the study area was determined by using equation given by Kasischke *et al.* (2005).

$$C_{p\text{-}a}(t) = B_a \times f_{c\text{-}a} \times F_{b\text{-}a} \times ß_{a(t)} \qquad (Eq.\ 6)$$

Where

$C_{p\text{-}a}$	Carbon release from the burning of aboveground biomass (tons)
B_a	biomass density (t/ha)
$f_{c\text{-}a}$	Carbon fraction of the biomass (0.47)
$F_{b\text{-}a}$	Fraction of the AGB that is available to burn (t/ha)
$ß_{a(t)}$	Fraction of the biomass consumed during fire (t)

The biomass density (B_a) was estimated from the field data, the carbon fraction of the biomass ($f_{c\text{-}a}$) value was derived from IPCC (2006), and the fraction of AGB available to burn (t/ha), i.e., $F_{b\text{-}a}$ was estimated by using the equation of Kasischke *et al.* (2005). According to Kasischke *et al.* (2005), where the total above ground biomass is low (<10 t/ha), 80% of the biomass is available to burn; where above ground biomass is moderate (10-20 t/ha), 50% is available to burn; and where above ground biomass levels is high (>20 t/ha), only 35% biomass is available to burn. The fraction of the biomass consumed during fire ($ß_a$) was estimated by dividing biomass consumed during forest fire by the biomass available to burn.

The equivalent carbon emission due to forest fire was estimated using the conversion factor from carbon mass to carbon compound mass, i.e., the equivalent carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH_4) (Trozzi *et al.*, 2002). The (CO_2) was estimated multiplying the carbon by 3.67. Similarly, carbon monoxide (CO) was determined by multiplying the carbon by 2.33 conversion factor and CH_4 was calculated by multiplying the carbon by 1.33 conversion factor (Trozzi *et al.*, 2002).

3.3.7 Estimation of biomass loss and damage

The biomass and carbon loss in the forest was estimated by taking the stock-difference between the non-burnt and burnt forests using the equation developed by IPCC (2006).

$CB = (C_{t2} - C_{t1})/(t_2 - t_1)$ *(Eq. 7)*

Where,

ΔC_B Annual change in carbon stocks in biomass (the sum of above-ground)

$C\ t_2$ Total carbon in biomass for each sample forest after forest fire at time t2 (Ct)

$C\ t_1$ Total carbon in biomass for each sample forest before forest fire at time t1 (Ct)

T_2 Biomass stock at time after forest fire

T_1 Biomass stock at time before forest fire

3.3.8 Data analysis

The statistical significance of each driver under different conditions affecting forest fire occurrence, carbon emission and loss of forest biomass were analyzed using Generalized Linear Model (GLM) with Poisson error structure. Likewise, difference in burnt area in different forests were analyzed using ANOVA. All the statistical analyses were performed in R-software Version 3.3.0 (R Core Team, 2016).

CHAPTER 4

4 RESULTS AND DISCUSSION

In this chapter, results obtained from the field and data analysis have been organized in accordance with the objectives, i.e., forest fire drivers and their contribution to the forest fire, biomass and carbon estimation, and loss and damage of forest biomass and carbon.

4.1 Forest fire occurrences

In Nepal, the spatial and temporal forest fire incidences and burnt areas were found to be varied for the period from 2001 to 2017. About 3,098 fire incidences burning 172,040.65 ha forest annually during the period (Fig. 14). The higher forest fire incidences and burnt areas were recorded in 2016 followed by 2014, 2010, 2012 and lowest in 2002. The highest forest fire in 2016 was due to higher temperature, lower precipitation and long dry period (Appenix XI).

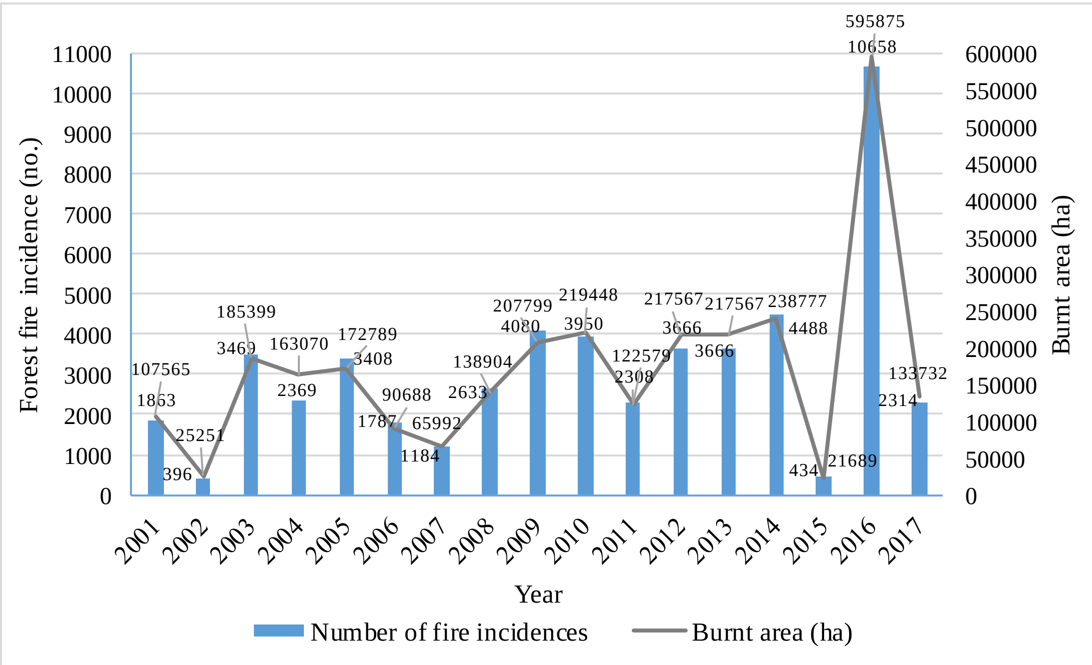

Figure 14: Forest fire trends in Nepal from 2001 to 2017

In Nepal, the density of forest fire incidences and burnt area varied with physiographic regions. The Tarai and Siwalik regions were found to be more fire vulnerable with higher forest fire density (Tarai with 0.09 fire incidence/km^2 and 4.74 ha/km^2 burnt area and Siwalik with 0.09 fire incidence/km^2 and 4.65 ha/km^2 burnt area) in compared to the High Mountain and Himalaya (0.01 fire incidence/km^2 with 1.57 ha/km^2 burnt area) and Middle hill (0.05 fire incidence/km^2 with 2.09 ha/km^2 burnt area) (Table 6).

Table 6: Forest fire densities by physiographic regions in Nepal

Physiographical region	Forest area (km^2)	Total fire incidence (no.)	Total burnt area (ha/yr)	Fire incidence (no./km^2)	Burnt area (ha/km^2)
High Mountain and Himalaya	24763	363	38854.19	0.01	1.57
Middle hill	23161	1131	48336.13	0.05	2.09
Siwalik	13964	1234	64898.92	0.09	4.65
Tarai	4211	372	19951.41	0.09	4.74

In Nawalparasi district, on average, 90 forest fire incidences and 3,151.6 ha forest burnt area was recorded annually during the period from 2001 to 2017 in the study area. The fire incidences showed a linear increasing trend ($p<0.05$) with forest burnt area (Fig. 15). The higher forest fires were recorded in the 2004, 2008, 2009, 2010 and 2016. The Hill Sal Forest showed more fire vulnerable due to higher annual forest fire occurrence (57 incidences with burnt area 2,281.9 ha) in compared to the Tropical Sal Mixed Broad-leaved Forest (31 fire incidences with 864.8 ha burnt area) and Riverine Forest (2 fire incidences with 4.8 ha burnt area) (Fig. 16, Table 7, Appendix X).

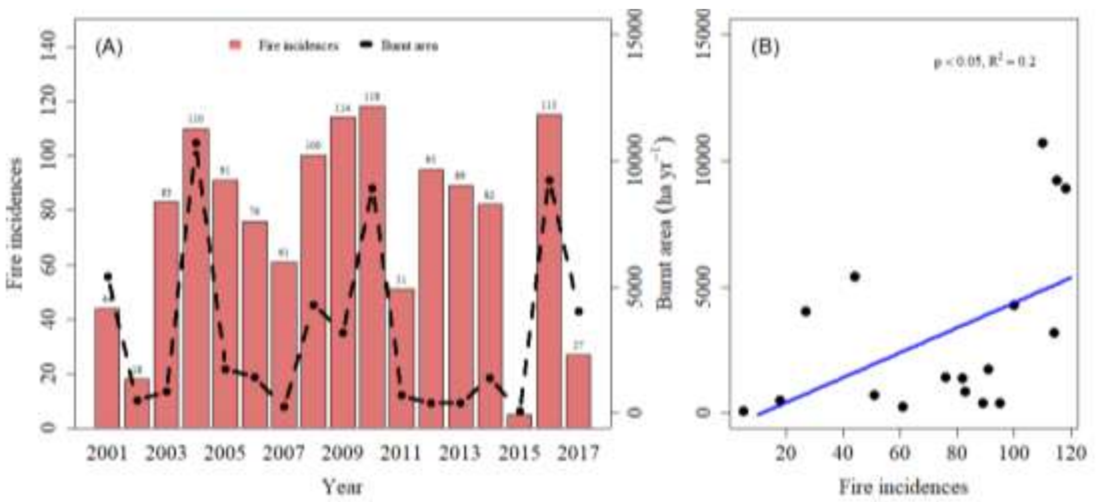

Figure 15: Status of forest fire incidences and burnt area, (A) Yearly variation of fire incidences and burnt area, (B) OLS regression between fire incidences and burnt area

Globally, about 345-464 Mha forest was recorded burned every year during the period from 1990s to 2000s (Randerson *et al.*, 2012). Similarly, on average about 0.081-0.125 Mha forest area was burned annually during the past two decades (1997-2016) in China

(Chen *et al.*, 2020). In India, around 3.73 million hectares forest get affected by fires annually (Satendra & Kaushik, 2014). Bhujel *et al.* (2017b) revealed that the higher forest fire density (0.09/km incidences, burnt area (3.4 ha/km^2) are in 2016 compared with the period of 2000-2015 (0.03/km^2 incidences and 1.4 ha burnt area/km^2) in Tarai region of Nepal.

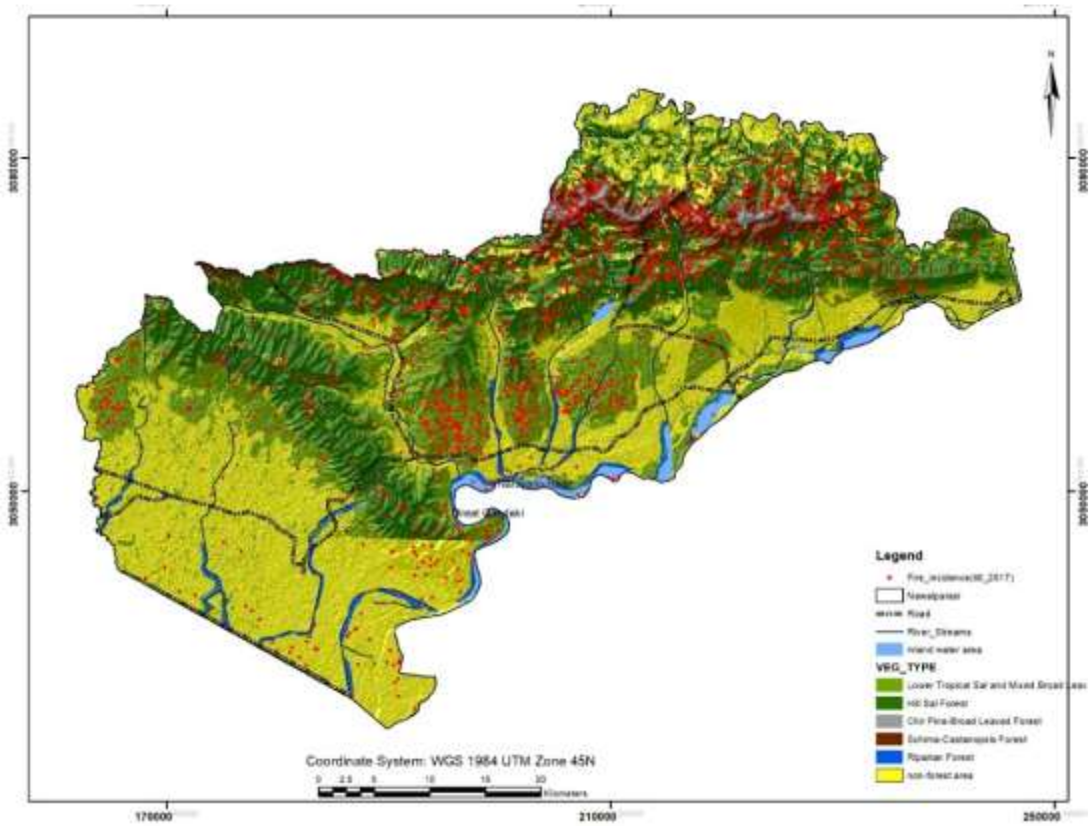

Figure 16: Forest fire incidences in different forest types

Table 7: Forest fire occurrence and burnt area (2001-2017) in different forest types

Forest fuel (biomass)	Total forest fire incidences (no.)	Total burnt area (ha)	Annual forest fire incidences (no.)	Annual burnt area (ha)	Burnt area per incidence (ha)
Lower Tropical Sal Mixed Broad-leaved Forest	533	14,701.6	31	864.8	27.89
Hill Sal Forest	970	38,792.3	57	2,281.9	40.03
Riveriene Forest	39	81.6	2	4.8	2.4
Total	1542	53,575.5	90	3,151. 5	35.01

4.2 Forest fire drivers

In the study area, 20 fire drivers causing forest fire were found (Fig. 17). Among them, eight were natural and 12 were anthropogenic drivers. The natural drivers include temperature, precipitation, humidity, forest fuel (biomass), aspect, elevation, slope and lightening. The anthropogenic drivers include forest distance from roads and settlements, wildlife poaching, non-timber forest product (NTFP) collection, smoking beehives, fuel-wood collection, camp-firing, cigarette butt, grass collection, throwing burning matches, trash fire and vehicular sparks.

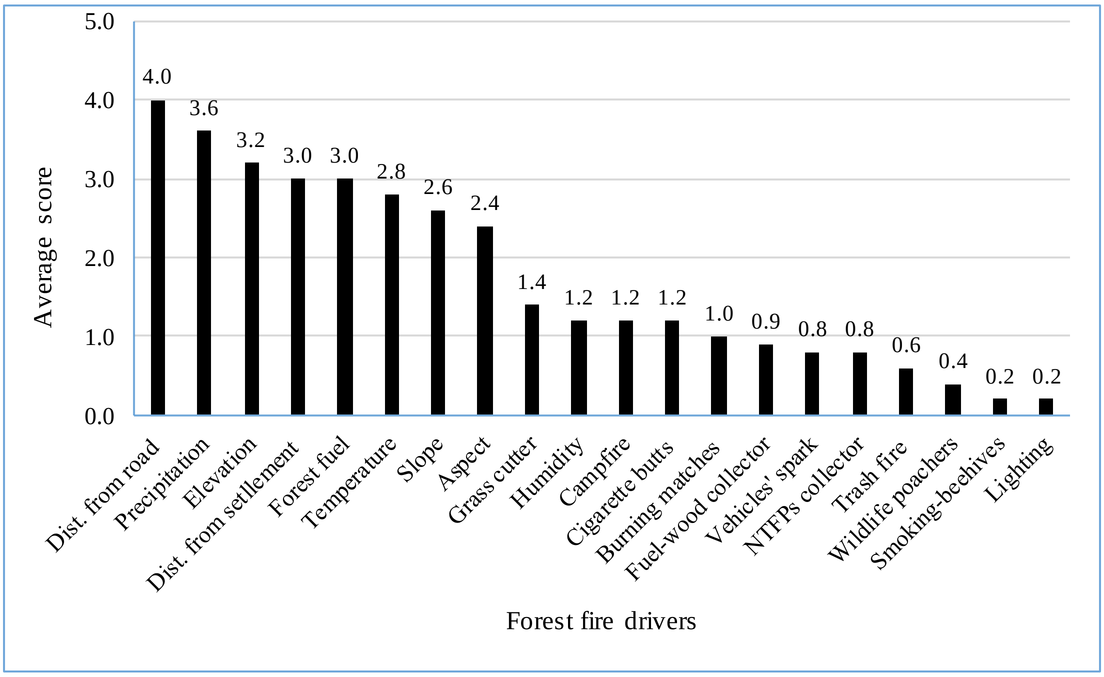

Figure 17: Forest fire drivers in Nawalparasi district

Among the various fire drivers, natural drivers like precipitation, elevation, temperature, slope, aspect and forest fuel; and among the anthropogenic drivers forest distance from roads and settlements were found to be the major drivers (Fig. 17, Appendix XI).

4.2.1 Natural drivers

Climatic drivers

The present study revealed that the forest fire occurrences vary with climatic conditions (temperature and precipitation) and topographic features (elevation, slope, aspect) of the forests. With respect to temperature, in the study area, the active fire season from 2001 to 2017 showed significant ($p<0.05$) higher forest fire occurrence (1,117 incidences in 17 years) with burnt areas 47,807.02 ha in temperature >30.0°C (Table 8, Appendix IX). Whereas, comparatively low forest fire occurrence (425 incidences in 17 years) with burnt areas 5,457.93 ha was found in the temperature <30.0°C. Similarly, in the relative humidity, during the 17 year period, higher forest fire occurrence (969 fire incidences and 47,977.40 ha burnt area) was found in the <78% relative humidity and comparatively low (573 fire incidences) and 5,598.25 ha burnt area in the >78% relative humidity in the study area.

This study revealed significant correlation (r values) between temperature and forest fire occurrences as reported by the various preceding studies (Abdi *et al*., 2016; Ahmad *et al*., 2017; Chen *et al*., 2014; Liu *et al*., 2012; Matin *et al*., 2017). According to Abdi *et al*. (2016), in Golestan of North East Iran, temperature showed significant positive correlation with forest fire occurrence. Similarly, in the Boreal Forests of North-east China, temperature showed positively correlation with the forest fire occurrence (Chen *et al*., 2014; Liu *et al*., 2012). Likewise, in the Jharkhand, India, Ahmad *et al*. (2017) observed strong positive correlation between the maximum temperatures, humidity with forest fire occurrence during the period from 2005 to 2016. In Nepal, the positive correlation between temperature >30°C and forest fires incidences has been reported by Matin *et al*. (2017).

The climatic drivers identified in the present study are in agreement with the findings of other preceding studies (Abdi *et al*., 2016; Ahmad *et al*., 2017; Chen *et al*., 2014; IPCC, 2014; Juárez *et al*., 2017; Leimgruber *et al*., 2011). Globally, the increased temperature has influenced the forest fire occurrence during the period of 2006-2015 in comparison to the 1850-1900 (IPCC, 2014). Similarly, Juárez *et al*. (2017) reported that the global climate change has influenced the forest fire occurrence in the tropical rainforests of South America, Asia, Australia and Africa during the period from 1981 to 2015. Likewise, Leimgruber *et al*. (2011) have reported the similar natural fire drivers in the tropical forests of South and South-east Asia. The similar natural fire drivers have been reported in Iran (Abdi *et al*., 2016), in China (Chen *et al*., 2014) and in India (Ahmad *et al*., 2017).

In terms of precipitation, in precipitation values less than 2400 mm, higher annual fire occurrences showed significant ($p<0.01$), i.e., 543 incidences with 26,155.85 ha burnt area in 17 years (annually 31 incidences with 1538.29 ha burnt areas) were found. However, in precipitation range from 2400 to 2800 mm, 504 fire incidences with 15,071.94 ha burnt area was found in 17 years accounting annual 30 incidences with 886.58 ha burnt area). In precipitation >2800 mm, lowest forest fire occurrence, i.e., 495 incidences with burnt area 12,347.82 was observed in 17 years (annual 29 incidences with burnt area 726.54 ha) (Table 8).

Table 8: Forest fire occurrences (2001-2017) caused by natural drivers

Forest fire drivers	Total forest-fire incidences (no.)	Total burnt area (ha)	Annual forest fire incidences (no.)	Annual burnt area (ha)	Burnt area per incidence (ha)
Temperature (ºC)					
<30.0	425	5,757.93	25	338.70	13.57
>30.0	1117	47, 817.26	66	2,812.78	42.60
Relative humidity					
>78%	573	5,598.25	33	329.35	9.98
<78%	969	47,977.40	57	2,822.20	49.50
Precipitation (mm)					
< 2,400	543	26,155.85	31	1,538.57	49.63
2,400-2,800	504	15,071.94	30	886.58	29.55
> 2,800	495	12,347.82	29	726.34	25.05
Aspect					
East	451	10,828.00	26	636.94	24.49
West	351	14,433.60	21	849.40	40.44
North	259	10,740.30	15	631.78	42.12
South	481	17,574.00	28	1,033.70	36.92
Slope (º)					
<15	495	17,175.80	29	1,010.34	34.84
15-30	280	29,224.20	16	1,719.07	107.44
>30	767	7,175.80	45	422.10	9.38
Elevation (m)					
<500	749	30,951.30	44	1,820.66	41.37
500-1000	562	17,609.80	32	1.035.87	32.37
>1000	231	5,014.70	14	294.98	21.07

These findings are in agreement with the several preceding studies (Bhujel *et al.*, 2018b; Charles & Steven, 2012; Chen *et al.*, 2014; Khanal, 2015; Matin *et al.*, 2017, Mondal *et al.*, 2015; Pausas, 2004; Prasad *et al.*, 2008). Charles and Steven (2012) found strong negative correlation between precipitation and forest fire occurrence in the forest of the South-eastern United States. Similarly, Pausas (2004) observed significant negative correlation between burnt area and summer precipitation in the Eastern Iberian Peninsula. Likewise, in China, Chen *et al.* (2014) and Liu *et al.* (2012) reported precipitation regime has significant negative correlation with forest fire occurrence for the period of 1982-1988 and 1989-2008, in five eco-regions of Yunnan Province. Moreover, Mondal *et al.* (2015), Ahmad *et al.* (2017) and Prasad *et al.* (2008) revealed negative correlation between precipitation and forest fire occurrence in India. In Nepal, strong negative correlation between precipitation and forest fire occurrence has been observed by (Bhujel *et al.*, 2018b; Khanal, 2015; Matin *et al.*, 2017).

Topographic drivers

The topographic features such as elevation, aspects and slope have influence on the forest fire occurrence and burnt areas. With respect to aspect, the significantly higher ($p < 0.001$) forest fire (annual 28 incidences with 1,033.7 ha burnt area) were observed in the Southern aspect (Figs. 18 & 19, Table 8, Appendix XII) which might be due to the longer exposure to solar radiation, longer dry period and accumulation of dry fuels. In the Eastern aspect, 26 annual forest fire incidences with 636.94 ha burnt area was found. The Eeastern and Northern aspects did not show significant variation in fire occurrences.

In Western aspects, 21 annual forest fire incidences with 849.4 ha forest burnt area was recorded. In Northern aspect, relatively less annual forest fire, i.e., 15 incidences with 631.78 ha burnt area, was found that may be due to shorter period of solar radiation, high moisture contents and accumulation of moist vegetation fuel (Fig. 20). The present findings are consistent with Alexander *et al.* (2006) who reported significant correlation between South-eastern aspect and forest fire occurrence in Klamath-Siskiyou region of Oregon and California.

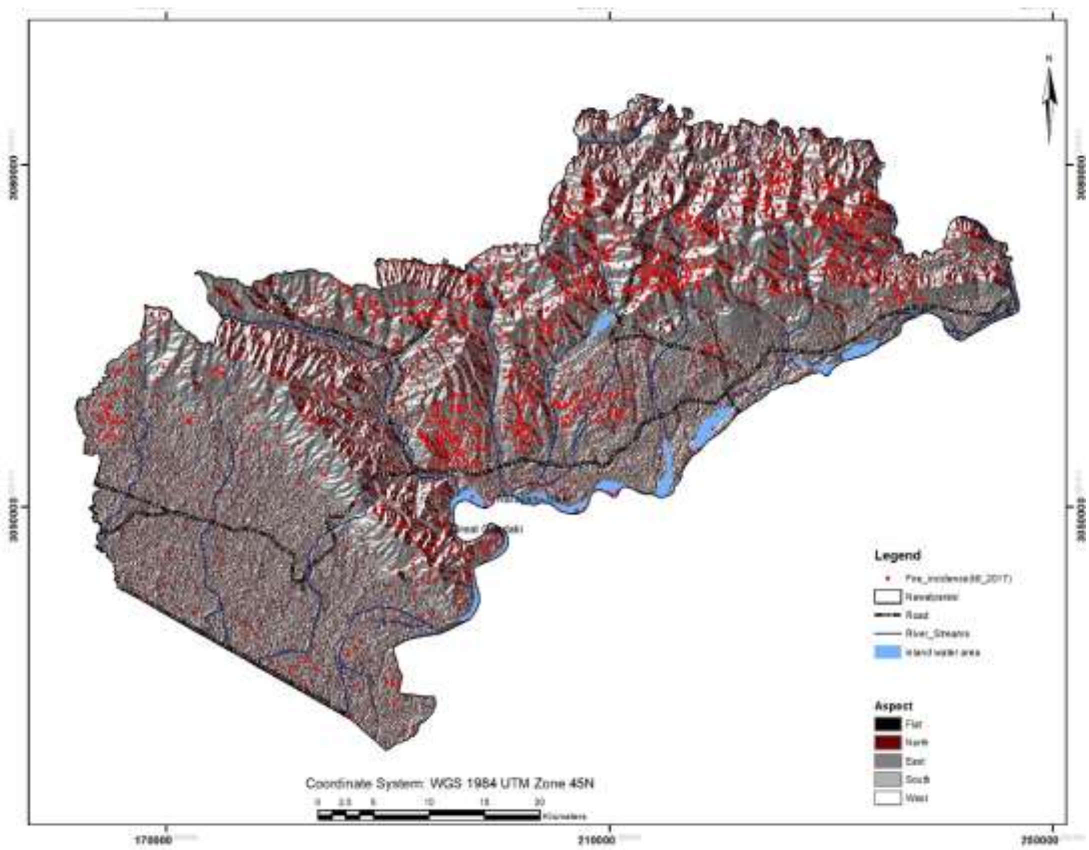

Figure 18: Variation of forest fire incidences with aspect

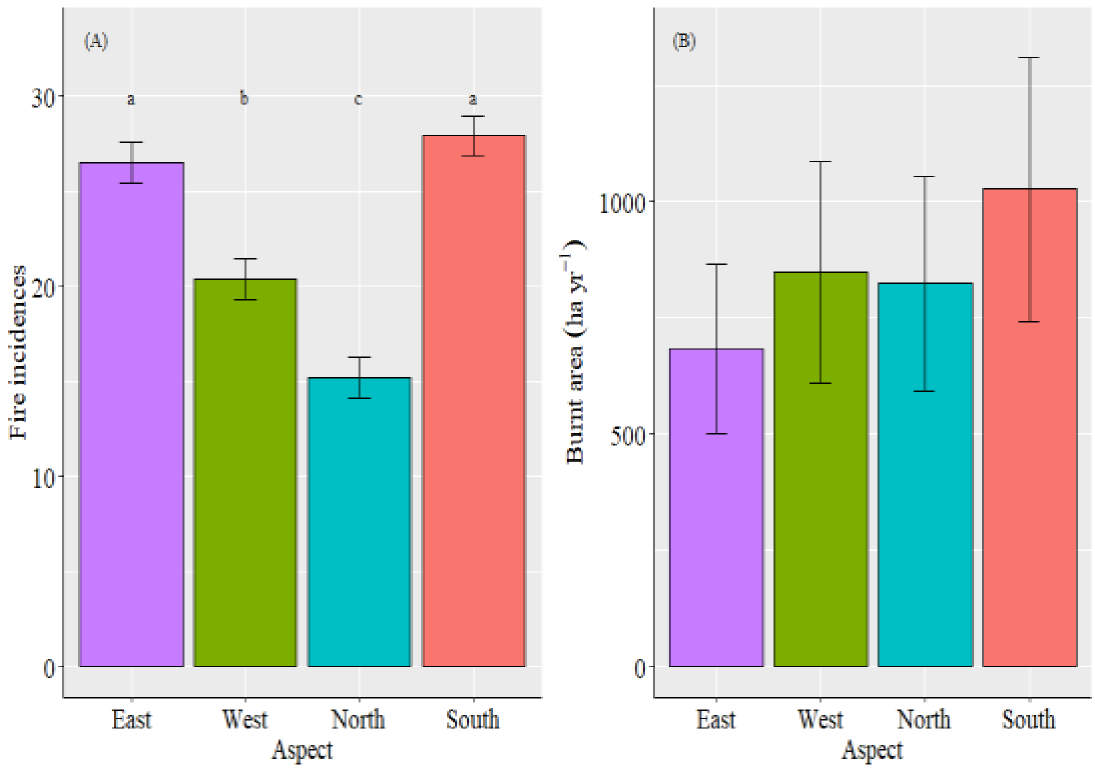

Figure 19: Aspect wise variations in annual fire incidences and burnt areas, (A) Yearly variation of fire incidences, (B) Yearly variation of forest burnt area, (common letter above bars represents means not significantly different, vertical lines represent standard errors)

With respect to slope, significantly higher ($p < 0.05$) forest fire occurrence was observed in the slope between 15% and 30% with 16 annual fire incidences and 1,719.07 ha burnt area in compared to slope >30% with 422.1 ha burnt area per year, which may be due to accumulation of higher amounts of forest fuels in the vertical structure of forest stands as well as due to human interferences (Figs. 20 & 21). Likewise, in the forest with slope value less than 15%, 29 annual fire incidences with 1010.34 ha forest burnt area were found. Similarly, the forest with slope >30% showed significantly ($p < 0.001$) higher, i.e., 45 annual forest fire incidences with 422.10 ha burnt area were found, which may be due to heterogeneity in the terrain structure (Fig. 21).

In South-eastern region of Australia, Bradstock *et al.* (2010) reported that forest fire is significantly correlated with slope. In Nepal, Matin *et al.* (2017) reported that the forests lying at less than 15% slope are significantly positively correlated with forest fire occurrence suggesting the forest in the lower slope to be highly susceptible to forest fire.

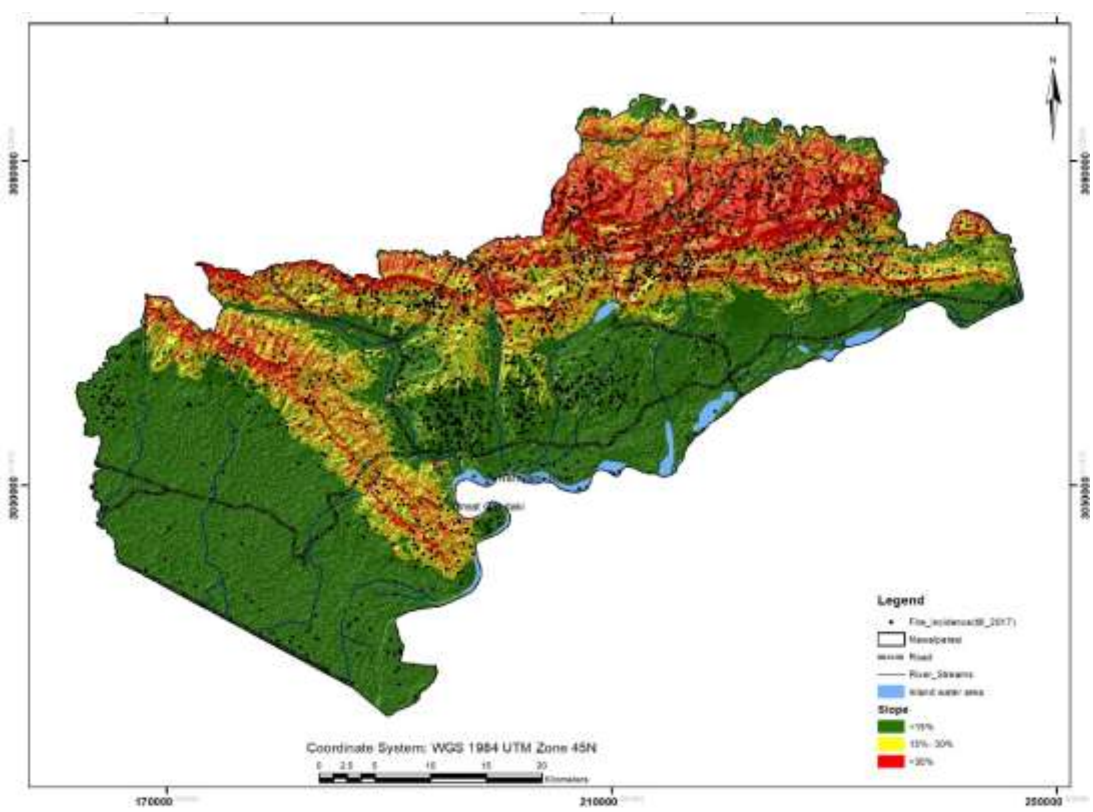

Figure 20: Variation of forest fire incidences with slope

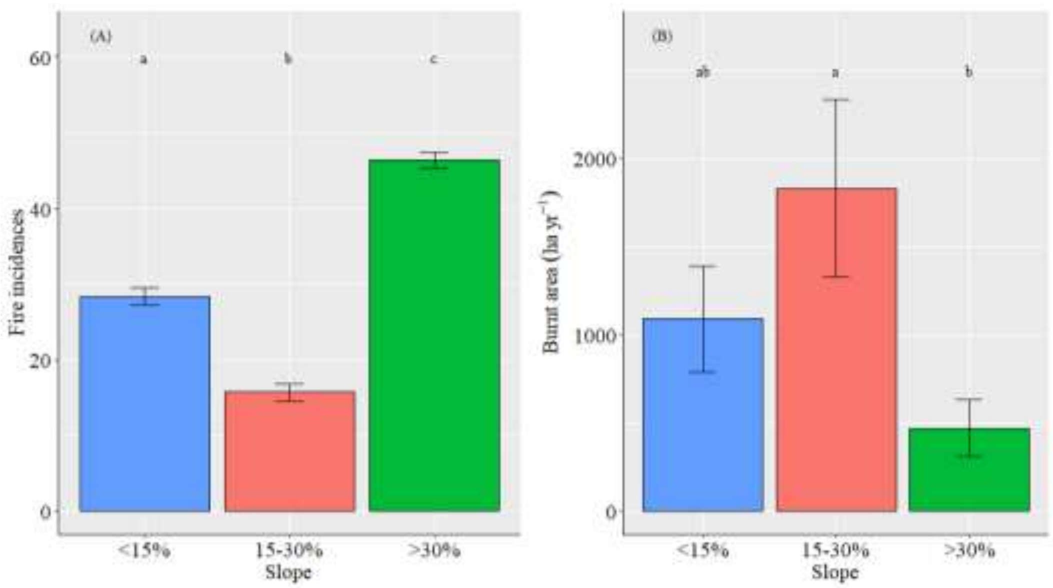

Figure 21: Slope wise variations of annual fire incidences and burnt areas, (A) Yearly variation of fire incidences, (B) Yearly variation of forest burnt area, (common letter above bars represents means not significantly different, vertical lines represent standard errors)

With respect to elevation, lower elevation (<500 m) showed significantly ($p<0.001$) higher annual fire occurrence (44 incidences) as compared to higher elevations, 500-1000 m and >1000 m (Figs. 22 & 23). The higher fire incidences in lower elevations might be due to the higher coverage of ground-level litter and vegetation. Likewise, 32 annual forest fire incidences were observed in the elevation range of 500-1000 m. In elevation range >1000 m, least annual forest fire (14 incidences) were found. In terms of annual burnt area, the elevation range <500 m showed significantly ($p<0.05$) higher burnt area (1,820.66 ha) than the elevation range >1000 m with burnt area 294.98 ha. However, no significant difference in annual burnt area was observed between elevation range 500-1000 m (1,035.87 ha) and <500 m (1,820.66 ha) and >1000 m (294.98 ha).

This finding is in agreement with Holden *et al.* (2011) who observed that lower elevation and south aspects have significant correlations with forest fire occurrence in Gila National Forest in New Mexico and Bitterroot National Forest in South-western Montana, USA. Similarly, Boreal Forest of China, Guo *et al.* (2015) reported that lower elevation has strong correlation with forest fire occurrence. In Nepal, Matin *et al.* (2017) reported that the forests lying in lower than 1000 m elevation are significantly positively correlated with forest fire occurrence suggesting the forest in lower elevation to be highly susceptible to forest fire.

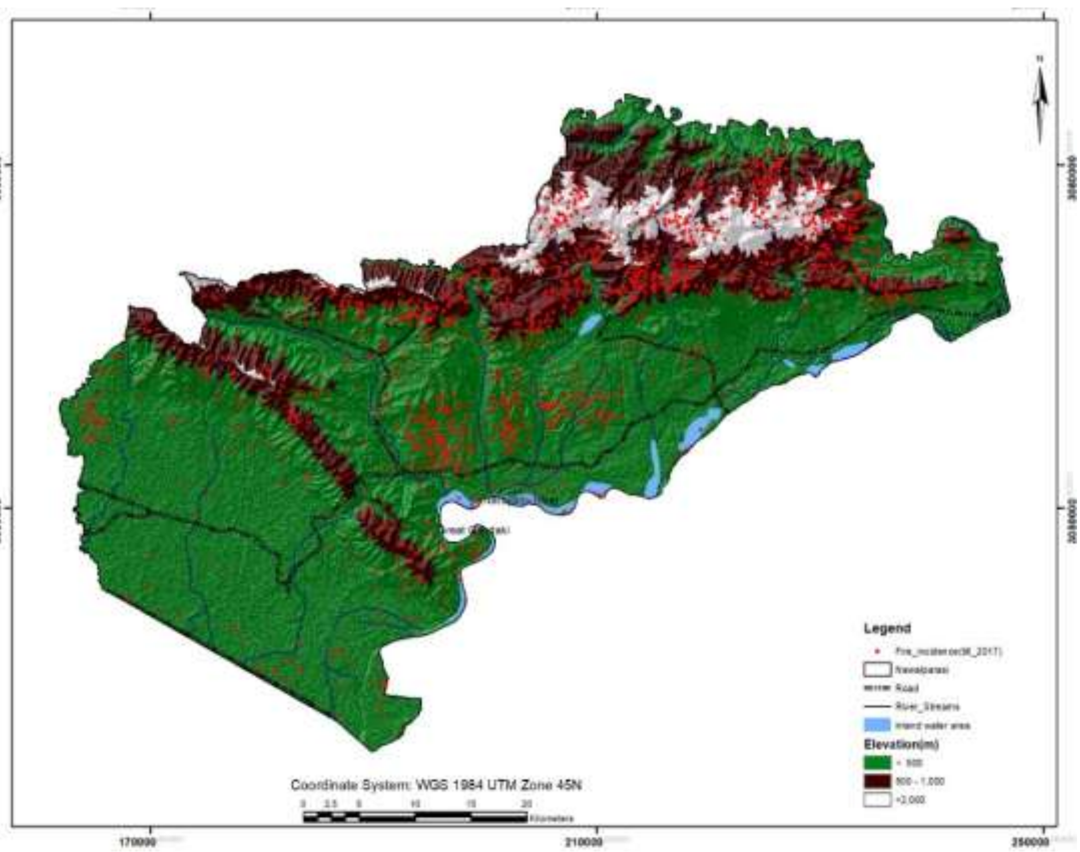

Figure 22: Variation of forest fire incidences with elevation

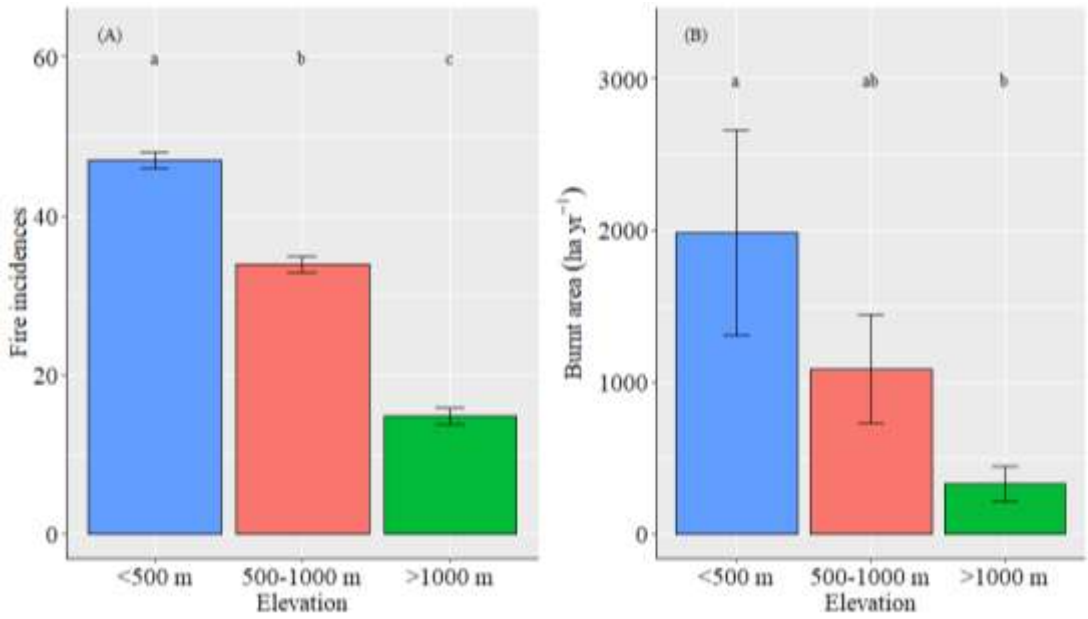

Figure 23: Elevation wise variations of annual fire incidences and burnt areas, (A) Yearly variation of fire incidences, (B) Yearly variation of forest burnt area, (common letter above bars represents means not significantly different, vertical lines represent standard errors)

The present findings pertaining topographic features (elevation, aspect and slope) are similar with the findings of various previous studies (Holden *et al.*, 2009; Iniguez *et al.*, 2008; Kumar *et al.*, 2015; Wood *et al.*, 2011). In Gila Wilderness and surrounding Gila National Forest of New Mexico, USA, Holden *et al.* (2009) observed elevation, aspect, slope and ruggedness as the major fire causing topographic factors for the period from 1984 to 2004. Similar results have been reported by Iniguez *et al.* (2008) in the Santa Catalina Mountains of South-eastern Arizona. Likewise, Wood *et al.* (2011) revealed similar results in the Eucalyptus forest and rain forest of Tasmania, Australia. Moreover, Kumar *et al.* (2015) have reported elevation, slope and aspect as the major factors for the forest fire in the Kangra region of Western Himalaya, India.

Forest fuel

The forest fire incidences and burnt areas vary with the characteristic of forest fuel (biomass) in the different types of forests. The results showed higher annual forest fire occurrence (57 incidences with burnt area 2,281.9 ha) in Hill Sal Forest (HSF) having 158.04 t/ha biomass as fuel that may be due to presence of higher amounts of fine fuel on the ground vegetation (leaf-litter, shrubs, herbs and grasses), trees, climbers. As these forest fuels are highly combustible, their accumulation in HSF has made the forest more vulnerable to fire. In the Lower Tropical Sal Mixed Broad-leaved Forest

(LTSMBF) having 284.58 t/ha biomass, annually 31 fire incidences with 864.8 ha burnt area were observed. The lesser forest fire occurrence in LTSMBF as compared to the HSF may be due to the presence of less fire prone matured tree and lower density of ground vegetation like shrubs, grasses and leaf-litters. Similarly, in Riverine Forest having 104.41 t/ha biomasses, least forest fire occurrences, i.e., annually only two fire incidences with 4.8 ha burnt area were observed (Table 9). This Riverine Forest is composed of almost even aged tree species with lower vertical vegetation structure.

This study is in agreement with the various preceding studies (Alvarez *et al.*, 2013; Badarinath & Vadrevu, 2011; Bergeron *et al.*, 2014; Chen *et al.*, 2008; Duff *et al.*, 2017; Johnson *et al.*, 2001; Liu *et al.*, 2008; Wu *et al.*, 2014). According to Alvarez *et al.* (2013), in North-east Iberian Peninsula, forest fuel is an important fire driver. In India, Badarinath and Vadrevu (2011) reported higher accumulation of forest fuel results in increased fire vulnerability in the Closed Broad-leaved Deciduous Forest and Closed Mixed Broad-leaved Forest. In the forest of the Southern Rockies, Canada, Johnson *et al.* (2001) reported positive correlation between spatial composition of vegetation type and fire occurrence. In Quebec's Southern Boreal Forest, Bergeron *et al.* (2004) reported positive correlation between forest fuel and forest fire occurrence. Likewise, in China, Chen *et al.* (2008) and Liu *et al.* (2008) observed accumulation of fine fuel influences the Boreal Forest fire; and Wu *et al.* (2014) revealed strong positive correlation between forest fuel composition and forest fire occurrence. Similarly, Duff *et al.* (2017) revealed that the fuel dynamics have an effect on worldwide fire regimes.

Table 9: Forest biomass (fuel) and fire incidences in different forests in 2014 and 2016

Forest types	Forest fuel (t/ha)	Forest fire (Incidences/yr)	Burnt area (ha/yr)
Lower Tropical Sal Mixed Broad-leaved Forest	285.58	31	864.8
Hill Sal Forest	158.04	57	2281.9
Riverine Forest	104.41	2	4.8

4.2.2 Anthropogenic fire drivers

The anthropogenic drivers are important drivers causing forest fire. Among the anthropogenic drivers, forest distance from roads and settlements are the major drivers for forest fire occurrence. With respect to forest distances from roads, the results revealed that the forests lying within 500 m distance from the roads has significantly ($p<001$) higher (69%) annual forest fire occurrence, i.e., 61 incidences with 81%

(2,562.76 ha) burnt area (Table 10, Fig. 24, Appendix XIII). The higher forest fires incidences in the areas nearby roads may be due to accumulation of fine fuel (bushes, shrubs, herbs and grasses) and human activities such as throwing burning match sticks and cigarette butts by the travelling bus passenger, grass cutters, campfires, a trash fire and exhaust sparks from the passing vehicles. The forest between 500 and 1000 m distance from the road revealed 21% annual forest fire occurrence, i.e., 20 fire incidences with 12% (371.0 ha) burnt areas. Likewise, the forest areas lying at distance more than 1000 m from the roads revealed 10% annual forest fire occurrence, i.e., 10 fire incidences with 7% (217.1 ha) burnt area. In this study, relatively less annual forest fire occurrence in distantly lying forest may be due to the inaccessibility of the area.

In terms of forest distance from the settlements, the forest lying within 500 m from the settlements showed significantly ($p<0.05$) higher (27%) annual forest fire occurrence with 25 fire incidences and 42% (1366.18 ha) burnt area (Table 10, Fig. 25). The forest lying in between 500 and 1000 m distance from the settlement showed lowest (36%) annual fire occurrence with 33 fire incidences and 26% (842.18 ha) burnt area. Similarly, the forest lying at distance more than 1000 m from the settlements showed 37% annual fire occurrences (33 fire incidences) with 31% (943.19 ha) burnt area. The higher fire incidences in the forest lying nearby settlements may be attributed to the presence of relatively high combustible forest fuels like shrubs, herbs, grass and their vigorous growth and higher human activities like grass cutters, herders, wildlife poachers and NTFPs collectors.

The present findings are consistent with the preceding studies from the different parts of the world (Adab *et al.*, 2013; Bowman *et al.*, 2011; Catry *et al.*, 2007; FAO, 2007; Guo *et al.*, 2015; Gralewicz *et al.*, 2012; Kasischke *et al.*, 2006; Lewis *et al.*, 2015; Liu *et al.*, 2012; Maingi & Henry, 2007; Niklasson & Granström, 2000; Oliveira *et al.*, 2012; Romero *et al.*, 2008; Syphard *et al.*, 2008; Wallenius *et al.*, 2004). Globally, Bowman *et al.* (2011) reported that the anthropogenic activities such as recreation (hiking, camping and hunting), settlements, roads and industry as the major forest fire drivers. According to FAO (2007), around 80% of the world's forest fire is caused by anthropogenic activities. Similarly, Lewis *et al.* (2015) reported that human-induced forest fire has increased in the recent years, threatening Tropical Forests across the world. In North Iran, Adab *et al.* (2013) reported that forest and grassland are more vulnerable to fire caused by the anthropogenic factors like forest distance from roads and settlements. In Portugal, Catry *et al.* (2007) reported that 70% of the forest fires occur near the settlements. Likewise, in Canada, Gralewicz *et al.* (2012) reported that forest fire occurrence is closely related to forest distance from roads and settlements. In the Alaskan Boreal Forest and forest in the Mediterranean Europe, Kasischke *et al.* (2006) and Oliveira *et al.* (2012) reported that the human causes and road density are significantly correlated with the forest fire occurrences.

In the Chinese Boreal Forest, Guo *et al.* (2015) and Liu *et al.* (2012) reported that forest fire occurrences are correlated with human activities such as landscape accessibility-proximity to settlements and roads. Moreover, Niklasson and Granström (2000) reported human-induced forest fire has increased in the Boreal landscape forest of Sweden from the last decades. In California and Kentucky, Romero *et al.* (2008), and Maingi and Henry (2007) reported that forests lying nearby settlement are more vulnerable to fire. Likewise, in the forest of Southern California, Syphard *et al.* (2008) have reported that forest fire occurrence is significantly correlated with anthropogenic activities like forest distance from the road. Furthermore, the forest fire occurrence has been strongly affected by human activities such as camping, hiking, hunting, settlements and roads in the Boreal Forest of the Northern Europe (Wallenius *et al.*, 2004).

Table 10: Forest fire occurrences (2001-2017) caused by anthropogentic drivers

Anthropogenic fire drivers	Total forest fire incidences (no.)	Total burnt area (ha)	Annual forest fire incidences (no.)	Annual burnt area (ha)	Burnt area per incidence (ha)
Distance from road					
<500 m	1044	43567.00	61	2562.76	42.01
500-1000	332	6307.00	20	371.00	18.55
>1000	166	3702	10	217.76	21.77
Distance from settlement					
<500 m	421	23225	25	1366.18	54.64
500-1000	553	14317	33	842.18	25.52
>1000	568	16034	33	943.19	28.58

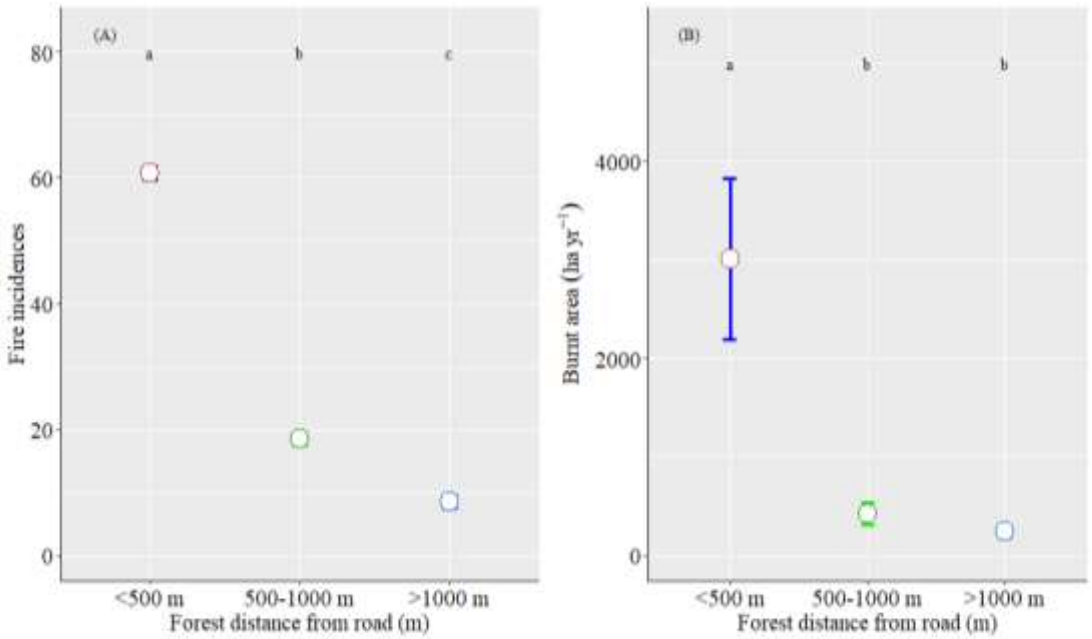

Figure 24: Annual forest fire incidences and burnt areas with distance from road, (A) Yearly fire incidences, (B) Yearly forest burnt area, (vertical lines represent standard errors)

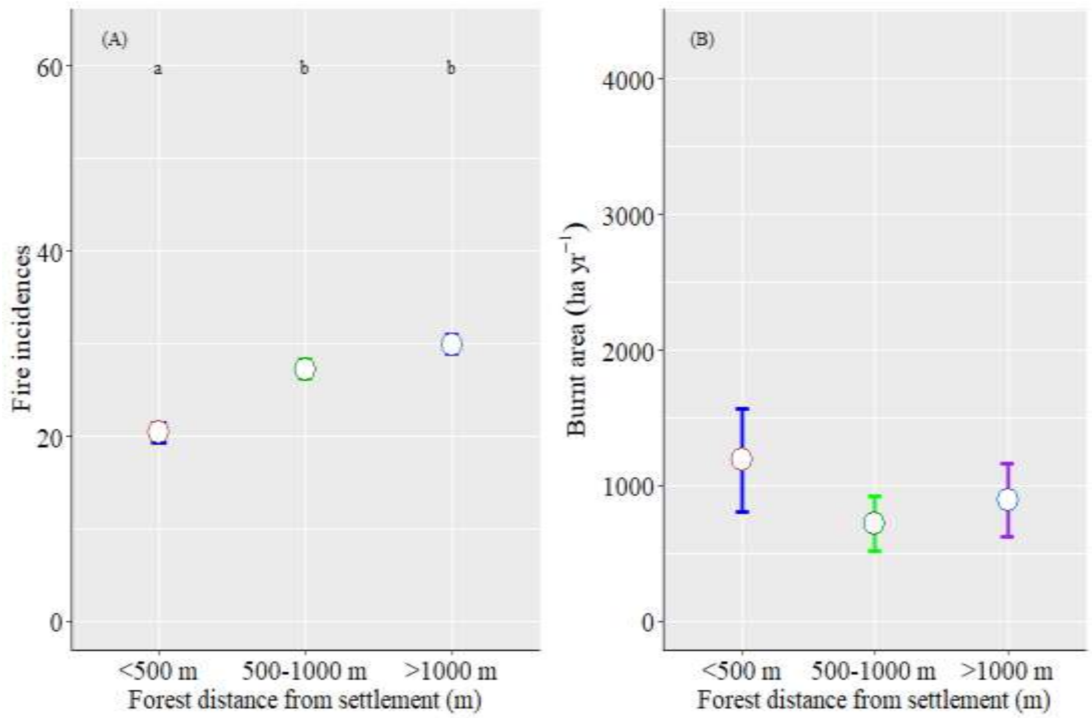

Figure 25: Annual forest fire incidences and burnt areas with distance from settlement, A) Yearly fire incidences, (B) Yearly forest burnt area, (vertical lines represent standard errors)

In Nepal, the human-induced fire drivers observed in the present study are similar to the preceding studies (Goldammer, 2003; Karkee, 1991; Kunwar & Khaling, 2006; Matin *et al*., 2017). Goldammer (2003) and Kanel (2007) reported that the increase in forest fire is due to human activities like fuel-wood collection, cattle grazing, honey collection, wildlife predation and non-timber forest product collection. Similarly, in the Terai region of Nepal, Kunwar and Khaling (2006) reported an increase in forest fire due to human activities. Likewise, Karkee (1991) observed that around 40% of forests fire in the Mid-hills of Nepal are caused by human activities like cattle grazing, honey collection, poaching and non-timber forest product collection. Moreover, Matin *et al.* (2017) reported that the forest lying within 1000 m from the settlements is highly vulnerable to fire.

4.3 Forest biomass and carbon

4.3.1 Forest biomass

The forest biomass varies with the forest types and growth stages. In the present study, in the Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF), the biomass of live and dead trees (DBH > 5 cm) was estimated to be 279.7 t/ha and 3.48 t/ha, respectively (Table 11). The biomass of sapling (DBH 1-5 cm) and Leaf-litter, Herbs and Grasses (LHG) were found to be 0.96 t/ha and 0.39 t/ha, respectively. Likewise, in the Hill Sal Forest (HSF), the biomass of live and dead trees (DBH > 5 cm) was estimated to be 153.71 t/ha and 1.18 t/ha, respectively. The biomass of sapling and LHG were found respectively to be 2.56 t/ha and 0.63 t/ha. Similarly, in the Riverine Forest (RF), biomass of live and dead trees (DBH > 5 cm) were found to be 102.58 t/ha and 0.98 t/ha, respectively. The results revealed the presence of higher tree biomass (live and dead) in the Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF) compared to the Hill Sal Forest (HSF) and Riverine Forest (RF). However, higher sapling biomass (2.52 t/ha) and Leaf-litter, Herbs and Grasses (LHG) biomass (0.63 t/ha) were found in the Hill Sal Forest. The higher tree biomass in the Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF) might be due to the presence of dense mature trees with less ground vegetation. The higher sapling and Leaf-litter, Herbs and Grasses (LHG) biomass in the Hill Sal Forest might be due to the higher density of sapling and leaf-litter, herbs, and grasses, which are more combustible. The results showed that the Hill Sal Forest is rich in combustible biomass making the forest more vulnerable to fire.

Table 11: Biomass in different forest types

Forest types	Trees biomass (t/ha)	Saplings biomass (t/ha)	Dead biomass (t/ha)	LHG (t/ha)	Total biomass (t/ha)
Lower Tropical Sal Mixed Broad-leaved Forest	279.75	0.96	3.48	0.39	284.58
Hill Sal Forest	153.71	2.52	1.18	0.63	158.04
Riverine Forest	102.58	0.38	0.98	0.47	104.41

The present results are consistent with various studies carried in India and Nepal (Baral *et al.*, 2010; Borah *et al.*, 2013; DFRS, 2015; Kumar *et al.*, 2011; Singh and Singh, 1991) possibly due to the similar bio-climatic conditions and vegetation types. Borah *et al.* (2013) have reported 32.5 to 261.6 Mg/ha above ground tree biomass in the Tropical Forest of Assam, India. Likewise, Kumar *et al.* (2011) have reported 30.0 to 346.0 Mg/ha above ground biomass in the forest of the Northern Haryana, India. Similarly, Singh and Singh (1991) have reported 7.1 to 21.0 t/ha biomass in the dry Tropical Forest of India. In Nepal, DFRS (2015) has reported 190.0 t/ha above ground air-dried biomass in the Terai and 172.2 t/ha in the Siwalik region. Similarly, Baral *et al.* (2010) have reported 217.5 t/ha and 178.8 t/ha above ground dry biomass in the Hill Sal Forest and Tropical Riverine Forest, respectively.

With respect to the Leaf-litter, Herbs and Grasses (LHG) biomass, the present study is not consistent with the other studies (Odiwe & Muoghalu, 2003; Sanches *et al.*, 2008; Singh *et al.*, 2011; Zhou *et al.*, 2006). Odiwe and Muoghalu (2003) reported annual 9.9-12.5 t/ha biomass of litter-fall in the lowland rainforest of Nigeria. Similarly, Sanches *et al.* (2008) reported annual 8.0 to 10.5 t/ha LHG biomass in the Tropical Semi-deciduous Forest of the Southern Amazon Basin, Brazil. Likewise, Zhou *et al.* (2006) reported 3.6 to 10.6 t/ha per year litter biomass in the Sub-tropical Monsoon Evergreen Broad-leaved Forest of China. Moreover, Singh *et al.* (2011) reported annual 8.2 to 8.8 t/ha litter-fall biomass in the Sub-tropical Forest of North India. The inconsistencies in LHG biomass observed in the present and other studies may be due to different bio-climatic conditions and different vegetation compositions.

4.3.2 Forest carbon

Among the forest types, the higher carbon content (133.8 t/ha) was found in the Lower Tropical Sal Mixed Broad-leaved Forest due to their higher biomass content. Similarly, 74.3 t/ha and 49.1 t/ha carbon were estimated in the Hill Sal Forest and Riverine Forest, respectively (Table 12). The present results are consistent with other previous studies (Baral *et al.*, 2010; Chhabra *et al.*, 2002; DFRS, 2015; Hertel *et al.*, 2009; Mohanraj *et al.*, 2011; Pande & Patra, 2010). According to Chhabra *et al.* (2002), there is 135.6 t/ha carbon stock in the forests of Jammu and Kashmir, India. In Indonesia, Hertel *et al.* (2009) have reported 128 Mg/ha carbon stock in the natural forest of Sulawesi. Similarly, Pande and Patra (2010) have reported 74.6 to 164 t/ha carbon in the forest of Dehradun, India. Likewise, on average 4.5 Tg carbon stock have been reported in the forest of Kolli hills, India (Mohanraj *et al.*, 2011). In Nepal, DFRS (2015) has reported around 104.5 t/ha and 97.7 t/ha carbon, in the forest of Terai and Siwalik regions, respectively. Similarly, Baral *et al.* (2010) have reported 97.9 t/ha and 80.5 t/ha carbon stock in the Hill Sal Forest and the Tropical Riverine Forest, respectively. The similar carbon stock found in the various previous studies may be due to the similar forest types and bioclimatic conditions.

Table 12: Above ground carbon stock in the different types of forest

Forest types	Biomass (t/ha)	Carbon (t/ha)
Lower Tropical Sal Mixed Broad-leaved Forest	284.58	133.75
Hill Sal Forest	158.04	74.26
Riverine Forest	104.41	49.06

4.3.3 Biomass available to burn

The biomass available to burn varies with the forest types. In the present study, the higher (99.60 t/ha) biomass available to burn was found in the Lower Tropical Sal Mixed Broad-leaved Forest in comparison to the Hill Sal Forest (55.31 t/ha) and Riverine Forest (36.49 t/ha) (Table 13).

Table 13: Biomass available to burn in different types of forests

Forest types	Biomass (t/ha)	Total biomass (tons)	Biomass available burn (t/ha)	Total biomass available to burn (tons)
Lower Tropical Sal Mixed Broad-leaved Forest	284.58	1,16,05,513.90	99.60	40,61,929.86
Hill Sal Forest	158.04	86,60,791.76	55.31	30,31,277.12
Riverine Forest	104.41	27,110.20	36.49	9,488.57

The biomass available to burn was found higher in the Lower Tropical Sal Mixed Broad-leaved Forest may be due to the presence of dense and matured tree composition compared to other forests.

4.3.4 Combustion efficiency

The fraction of the biomass consumed during the fire and biomass available to burn is referred as the combustion efficiency, which varies according to the forest types. The results revealed higher combustion efficiency (1.57%) in the Hill Sal Forest, followed by the Riverine Forest (0.87%) and the Lower Tropical Sal Mixed Broad-leaved Forest (0.60%) (Table 14). The reasons for the higher combustion efficiency in the Hill Sal Forest might be due to the presence of larger amount of fine combustible materials compared to the Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest. The present results revealed low combustion efficiency compared to the IPCC (1997), Kasischke *et al.* (2005) and Venkataraman *et al.* (2006). According to IPCC (1997), 0.60% combustion efficiency has been reported for all types of forest in Asian continent. Similarly, Kasischke *et al.* (2005) have reported 0.4% combustion efficiency during the surface fire. Moreover, Venkataraman *et al.* (2006) have reported on average 0.50% combustion efficiency for the dense forest of India. The combustion efficiency observed in the present study is inconsistent with preceding studies which may be due to the specific forest types of particular location considered for the study and consideration of the continental level different forest types in the other studies.

Table 14: Biomass combustion efficiency in different forests

Forest types	Total biomass (t/ha)	Biomass available to burn (t/ha)	Biomass consumed (t/ha)	Combustion efficiency*	Combustion efficiency (%)
Lower Tropical Sal Mixed Broad-leaved Forest	248.58	99.60	0.60	0.006	0.60
Hill Sal Forest	158.04	55.31	0.80	0.0150	1.57
Riverine Forest	104.41	36.50	0.30	0.0087	0.87

*Ratio between biomass consumed during the fire and biomass available to burn

4.3.5 Carbon emission

Forest fire has become one of the important factors contributing atmospheric carbon. Forest fires have become one of the most important factors contributing to atmospheric carbon dioxide. In the present study, an average of 1107.80 tons (0.40 t/ha/yr) of total carbon emissions was found annually for the period from 2001 to 2017 (Table 15). Among the forest types, there was relatively high carbon emissions (824.10 t/yr, i.e., 0.40 t/ha/yr) from the Hill Sal Forest compared to the Lower Tropical Sal Mixed Broad-leaved Forest (282.50 t/yr, i.e., 0.30 t/ha/yr) and Riverine Forest (1.20 t/yr, i.e., 0.20 t/ha/yr), which may be attributed to the higher accumulation of forest fuels as well as to human activities in the Hill Sal Forest. With regards to equivalent carbon emissions, the total annual emission was equivalent to 4065.70 t CO_2, 2581.20 t CO and 1474.10 t CH_4. Among the forest types, the highest emissions (3024.50 t CO_2, 1920.20 t CO and 1096.80 t CH_4) were produced by the Hill Sal Forest compared to the Lower Tropical Sal Mixed Broad-leaved Forest (1036.80 t CO_2, 6580.2 t CO and 375.70 t CH_4) and the Riverine Forest (4.40 t CO_2, 2.80 t CO and 1.60 t CH_4) (Table 15).

The present finding is similar with the various preceding studies (Badarinath & Vadrevu, 2011; Kasischke & Bruhwiler, 2003; Lu *et al.*, 2006; Sibanda, 2011; Venkataraman *et al.*, 2006; Yin *et al.*, 2019; Zhang *et al.*, 2016). According to Kasischke and Bruhwiler (2003), 290.00 to 383.00 Tg of the total carbon emission (equivalent 828.00-1103.00 Tg CO_2, 88.00-128.00 Tg CO and 2.90-4.70 Tg CH_4) was reported from the Boreal Forest fire of five different regions of the North America and Russia. Similarly, in China, Zhang *et al.* (2016) have reported 0.04-7.22 Tg annual carbon emission due to forest fire for the period from 1988 to 2012, and on average 40.80 Tg per year CO_2 emission was reported from the forest fire for the period from 2003 to 2017 (Yin *et al.* 2019). Similarly, Badarinath and Vadrevu (2011) have revealed 6.34 Tg annual CO_2 emissions from the forest fire in India. In Nepal, Sibanda (2011) has reported 1669.00 Mg/ha annual carbon emission from the forest of Ludikhola (Middle-hill) Watershed of Gorkha District for the year 2008.

Table 15: Carbon emission in different types of forest

Forest types	Total burnt area (ha/yr)	Carbon emission (t/yr)	Carbon emission (t/ha/yr)
Lower Tropical Sal-mixed Broad-leaved Forest	882.70	282.50	0.30

Hill Sal Forest	2263.90	824.10	0.40
Riverine Forest	4.90	1.2	0.20
Total	3151.50	1,107.80	0.40

Table 16: Equivalent annual carbon emission in different types of forest

Forest types	**CO_2 emission (t/yr)**	**CO emission (t/yr)**	**CH_4 emission (t/yr)**
Lower Tropical Sal-mixed Broad-leaved Forest	1036.80	658.20	375.70
Hill Sal Forest	3024.50	1920.20	1096.80
Riverine Forest	4.40	2.80	1.60
Total	4065.70	2581.20	1474.10

4.4 Loss and damage of forest

4.4.1 Loss of forest biomass and carbon

In Nepal, approximately 172,040.65 ha forest burnt annually during the period from 2001 to 2017. In Nawalparasi district, annually 3151.50 ha forest burning during the period of 17 years. Approximately, 0.49 t/h, 0.79 t/h, 0.30 t/ha biomass and 0.23 t/ha, 0.37 t/ha, 0.14 t/ha carbon were found to be lost in the Lower Tropical Sal Mixed Broad-leaved Forest, Hill Sal Forest and Riverine Forest, respectively (Table 17). In total, 2,360.56 tons annual biomass and 1,108.47 tons annual carbon was found to be lost. The higher loss of annual biomass (1,857.54 t) and carbon (873.05 t) were found in Hill Sal Forest compared to the Lower Tropical Sal Mixed Broad-leaved Forest (501.27 t/yr biomass and 235.0 t/yr carbon) and Riverine Forest (1.70 t/yr biomass and 0.82 t/yr carbon).With respect to relationship between burnt area, and biomass and carbon loss, the analysis showed significant positive correlation ($R^2 = 0.952$, Pearson's (r) = 0.975, $p < 0.05$). This suggests that the loss of the biomass is influenced by the burnt area.

Table 17: Loss of biomass and carbon from forest fire

Forest types	**Forest area (ha)**	**Burnt area/(yr)**	**Biomass loss (t/ha/yr)**	**Carbon loss (t/ha/yr)**	**Biomass loss (t/yr)**	**Carbon (t/yr)**
Lower Tropical Sal Mixed Broad-leaved Forest	40781.2	864.8	0.49	0.23	501.27	235.00
Hill Sal Forest	54808.2	2281.9	0.79	0.37	1857.54	873.05
Riverine Forest	260	4.8	0.30	0.14	1.70	0.82
Total	95849.4	3151.5	1.60	0.84	2360.56	1108.47

The present results are in agreement with the various previous studies (Badarinath & Vadrevu, 2011; Chang & Song, 2010; Hoelzemann *et al.*, 2004; Keith *et al.*, 2014; Yi

& Bao, 2016). According to Hoelzemann *et al.* (2004), in Southern Asia, annually, 18.7 Tg CO_2 lost due to forest fire in the year 2000. Similarly, Chang and Song (2010) have reported 5.00 Tg annual CO_2 loss due to surface fire of forest of the Tropical Asia. Likewise, Keith *et al.* (2014) have reported that around 3.90 Tg carbon (8.5%) loss for the year 2009 due to forest fire in Australia. In China, Yi and Bao (2016) have reported about 4-11% carbon loss from the forest fire in the shrub-land, grass and Boreal Forest region. Moreover, Badarinath and Vadrevu (2011) have estimated around 6.34 Tg annual carbon loss from forest biomass burning in India.

4.4.2 Damage of the forest resources

In Nepal, total 29,24,691.05 ha forest was found to be burnt during the period from 2001 to 2017 (Tables 8 & 18, Appendix XIV). In annually, 1,72,040.65 ha/yr forest was found to be burnt for the period of 17 years. The higher forest damage was found in Tarai (4.73 ha/km^2) and Siwalik (4.73 ha/km^2) in compared to High mountain and himalaya and Middle hill.

Table 18: Forest damage in different physiographic regions

Physiographic regions	Forest area (km^2)	Total burnt (ha)	Total burnt (ha/yr)	Burnt area (ha/km^2)
High mountain and Himalaya	24,763	6,60,521.23	38,854.19	1.56
Middle hill	23,161	8,21,714.21	48,336.13	2.08
Siwalik	13,964	11,03,281.64	64,898.92	4.64
Terai	4,211	3,39,173.97	19,951.41	4.73
Total	66,099	29,24,691.05	1,72,040.65	

In the present study forests, on average, 3,151.50 ha forest was found to be damaged annually due to surface fire. The leaf-litter, herbs and grasses were found to be severely damaged accounting >90% biomass loss. Similarly, around 0.01-0.4% of tree biomass, 2-5% of pole size plant biomass and 5-10% sapling biomass were found to be damaged due to forest fire (Table 19). Generally, the surface fire caused severe damage to the ground vegetation and sapling, and less damage to tree stands.

Table 19: Damage of different plants types in the forests

SN	Forest/vegetation class	Damage (%)
1	Leaf-litter, herbs and grass (LHG)	>90

2	Sapling (DBH 1-5 cm)	5-10
3	DBH >5 cm (up to tree)	0.01-5.00 (2-5% pole, 0.01-0.4% tree)

The present study results are consistent with various preceding studies (DFRS, 2015; FAO, 2007; Liu *et al*., 2019; Schmerbeck & Fiener, 2015). According to Liu *et al*. (2019), around 15% of global forest loss due to forest fire accounts during the period from 2003 to 2014. Similarly, FAO (2007) has reported over 350 million ha (6%) forests damage across the world due to forest fire in 2000. Likewise, Schmerbeck and Fiener (2015) have reported that annually, around 1.4% of Tropical Deciduous Forest damage due to forest fire in India. In Nepal, around 27.8% of forest has been reported to be affected by the forest fire (DFRS, 2015).

CHAPTER 5

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In Nepal, about 3098 fire incidences burning 172,040.65 ha forest annually during the period from 2001 to 2017. Among five types of forests in Nawalparasi district, the Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF), Hill Sal Forest (HSF) and Riverine Forest (RF) are high value forest vulnerable to forest fire caused by various natural and human-induced drivers. In Nawalparasi district, 3151.05 ha forest per year were found to be damaged. Among the forest types, the Hill Sal Forest was the most vulnerable in compared to the Lower Tropical Mixed Broad-leaved Forest and Riverine Forest. There are 20 forest fire drivers, including eight natural and 12 human-induced drivers. Among the 20 drivers, eight are the major forest fire contributing drivers, which includes six natural and two human-induced. The major six natural drivers include temperature, precipitation, forest fuel, aspect, elevation and slope. Likewise, two human-induced drivers include forest distance from road and settlement. With respect to contribution of fire drivers to forest fire, among the natural drivers, precipitation and elevation have higher contribution. In connection to anthropogenic drivers, forest distance from the road is the highly contributing driver. The forest lying within 500 m distance from road is highly fire prone, while forest lying at the distance beyond 1000 m from road is less prone to fire. With respect to topographic drivers, forest lying at the lower elevation (<500 m), south and east aspects, >30ºC temperature and <2400 mm annual precipitation is more fire prone.

The Lower Tropical Sal Mixed Broad-leaved Forest has higher tree biomass in comparison to Hill Sal Forest and Riverine Forest. There is the higher sapling and LHG biomass in Hill Sal Forest in comparision to the Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest. The carbon stock shows similar trends in these forests. Similarly, there is larger burnt area in Hill Sal Forest as compared to the Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest. Considering combustion efficiency, there is higher combustion efficiency (1.57%) in the Hill Sal Forest as compared to the Riverine Forest (0.87%) and the Lower Tropical Sal Mixed Broad-leaved Forest (0.60%).

In terms of emission, 1108 tons/year carbon was found to be emitted due to forest fire in Nawalparasi district that is equivalent to approximately 4066 t CO_2, 2581 t CO and 1474 t CH_4.With respect to plant forms, higher (>90%) damage was found in leaf-litter, herbs and grass as compared to trees (0.01-0.4%). The relatively high carbon (equivalent CO_2, CO, CH_4) emission was found in the Hill Sal Forest compared to the Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest.

5.2 Recommendations

Based on the findings of the present study, the following recommendations have been made:

1. The present results revealed that anthropogenic drivers like forest distance from road and settlement are highly forest fire contributing drivers. Thus, human-induced fire activities need to be controlled through enhanced awareness, capacity building, and formal and informal education programs for the better response of the community and the local government for sustainable forest fire management.

2. Among the forest types, the burnt area is higher in Hill Sal Forest resulting in more carbon emission. Thus, for better forest fire prevention and control, sufficient fire lines and conservation ponds required to be constructed.

3. Biomass was estimated using allometric equations previousely developed for different forest types. Thus, for reliable and precise data, country specific species-wise equations need to be developed.

4. In the present study, the combustion factor was estimated from different types of forest of the Nawalparasi district only. Thus, for developing national combustion factor, further detailed study needs to be carried out in different forest types of Nepal.

5. Above ground biomass available to burn was estimated according to Kasischke *et al.* (2005). Thus, for consistent and precise data, country specific forest types wise method to estimate above ground biomass available to burn need to be developed.

CHAPTER 6

6 SUMMARY

Forest fire is increasing globally in recent years due to natural and anthropogenic causes threatening forest ecosystems and environment. In Nepal, substantial forest area, biomass and carbon is lost due to fire. The high value lowland forests of Nepal are more vulnerable to fire caused by various fire drivers. However, there are limited studies on estimation of biomass loss and carbon emission due to forest fire. Thus, the present research was carried out to estimate forest fire area in different ecological regions of Nepal, and biomass loss and carbon emission from the Tropical Mixed Broad Leaf Forest of Nawalparasi district. The forest fire drivers were identified through Focus Group Discussion (FGD-6), Key Informant Interview (KII-10) and Consultation Meeting (5) with 39 individuals, professionals and stakeholders. The identified fire drivers were prioritized and ranked by scoring method. The highest scoring drivers were selected for further studies. The spatial and temporal forest fire occurrences and burnt areas were used for assessing fire driver's contribution to forest fire. Forest fire incidences and burnt area for 2001-2017 were acquired from MODIS fire data. The burnt and non-burnt area were delineated using GIS program. Similarly, data related to road networks, settlements and topography were obtained from the Survey Department, Government of Nepal. Climate data (temperature,humidity and precipitation) were collected from the Department of Hydrology and Meteorology, Government of Nepal. The digital maps of forest types were acquired from the Department of Forests and Soil Conservation, Government of Nepal. The tree and sapling biomass (fuel) was estimated through field survey using allometric equation of Chave *et al.* (2005) and seedling biomass of tree species was estimated according to Tamrakar (2000). The forest fire incidences and burnt areas were calculated using ArcGIS. The significance of each driver affecting forest fire occurrence under different conditions were assessed using Generalized Linear Model (GLM) with Poisson error structure. Likewise, differences in burnt area in different forests were analyzed using ANOVA. All the statistical analyses were performed in R-software Version 3.3.0 (R Core Team, 2016).

For determining biomass loss and carbon emission, the Kasischke *et al.* (2005) allometic equation was used for determining the biomass loss and carbon emission. The biomass density was estimated from the field data, the carbon fraction of the biomass value was derived according to IPCC (2006), and the fraction of AGB available to burn (t/ha) was estimated by using the equation of Kasischke *et al.* (2005). According to Kasischke *et al.* (2005), where the total above ground biomass is low (<10 t/ha), 80% of the biomass is available to burn; where above ground biomass is moderate (10-20 t/ha), 50% of the biomass is available to burn; and where above ground biomass levels is high (>20 t/ha), only 35% biomass is available to burn. The fraction of the biomass consumed during fire was estimated by dividing biomass consumed during forest fire by the biomass available to burn. The biomass and carbon loss in the forest was estimated by taking the stock-difference between the non-burnt and burnt forests using the equation developed by IPCC (2006). The equivalent carbon emission due to forest fire was estimated using the conversion factor from carbon mass to carbon compound mass, i.e., the equivalent carbon carbon dioxide (CO_2), monoxide (CO) and methane (CH_4) following Trozzi *et al.* (2002).

The results revealed 29,24,691.05 ha forest (1,72,040.65 ha with 3,098 fire incidences/yr) to be damaged in Nepal from 2001 to 2017. In Nawalparasi district, 3151.05 ha forest per year were found to be damaged. Among the forest types, the Hill Sal Forest was the most vulnerable in compared to the Lower Tropical Mixed Broad-leaved Forest and Riverine Forest. In the study area, the Lower Tropical Sal Mixed Broad-leaved Forest (LTSMBF), Hill Sal Forest (HSF) and Riverine Forest (RF) were vulnerable to forest fire likely to be caused by various natural and human-induced drivers. Altogether, 20 forest fire drivers were found and among them eight drivers, six natural and two human-induced, were found to be the major drivers. Among the natural drives, temperature, precipitation, aspect, slope, elevation and forest fuel are the major one. Among the anthropogenic drivers, forest distance from roads and settlements are the major drivers. The forest lying in the lower elevation <500 m, south and east aspects were more fire prone. Temperature greater than 30ºC and annual precipitation <2400 mm were found to be favorable for forest fire. Similarly, the forests lying within 500 m distance from the road were highly fire vulnerable. This suggests that the Hill Sal Forest is highly vulnerable to forest fire due to the higher accumulation of forest fuel and anthropogenic activities.
Thus, fire awareness and mitigation activities should be conducted at the local level also.

In terms of biomass and carbon, the forests of Nawalparasi district revealed higher tree biomass and carbon in the Lower Tropical Sal Mixed Broad-leaved Forest in comparison to the Hill Sal Forest and Riverine Forest. The Hill Sal Forest contains higher combustible materials (sapling and LHG biomass) compared to the Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest. In connection to burnt area, there is larger burnt area in the Hill Sal Forest in compared to the Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest. With respect to combustion efficiency, the Hill Sal Forest showed higher combustion efficiency (1.57%) in comparison to the Riverine Forest (0.87%) and the Lower Tropical Sal Mixed Broad-leaved Forest (0.60%). In terms of emission, 1108 tons/year carbon was found to be emitted due to forest fire in Nawalparasi district that is equivalent to approximately 4066 t CO_2, 2581 t CO and 1474 t CH_4. With respect to the equivalent carbon (CO_2, CO, CH_4) emission, the Hill Sal Forest showed higher emission compared to the Lower Tropical Sal Mixed Broad-leaved Forest and Riverine Forest. The ground vegetation (leaf-litter, herbs and grasses) was observed highly damaged accounting >90% biomass loss. Likewise, around 0.01-0.40% of tree biomass, 2.0-5.0% of pole size tree biomass and 5.0-10.0% sapling biomass were found to be damaged due to forest fire.

Among the forests, the Hill Sal Forest is more vulnerable to fire resulting higher carbon emission due to higher accumulation of forest fuels and anthropogenic activities. Thus, for the sustainable forest management, adequate fire-lines and conservation ponds are required to be constructed along with capacity building and awareness raising program for the local community and forest fire watch groups. Similarly, the allometric equations, used in the present study were developed for general forest types, thus for determining reliable and precise biomass data, country specific species-wise equations need to be developed.

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APPENDIXES

Appendix I: Photographs of different forest types in the study area

Lower Tropical Mixed Broad-leaved Forest

Hill Sal Forest

Hill Sal Forest

Riverine Forest

Appendix II: Checklist for identifying fire drivers and their prioritization

Q # 1. What are drivers of forest fire occurrence and burnt area, please list out?

SN	Drivers of forest fire occurrence	Remarks
1		
2		
3		

Prioritization of drivers of forest fire occurrence: using scoring method.

List of forest fire drivers	Fire frequency (score)				Fire severity of forest vegetation (score)				Total
	0	1	2	3	0	LGH (1)	Up to 2 m (2)	>2 m (3)	

Basic criteria for scoring based on the fire frequency and fire severity

1. Fire frequency scoring

   0 = none, 1= one time, 2= two types and 3 = three times fire occurrence a year

2. Forest fire severity

   0 = none severity, 1= severity of LHG, 2= severity vegetation up to two meter height 3 = severity of forest vegetation > two meter height.

Prioritization of forest fire drivers

SN	Forest fire drivers	Total scoring	Scoring in percentage (%)
1			
2			
3			

Q # 2. What are history of forest fire occurrence and burnt area?

Q # 3. What are loss and damage of forest resources due to forest fire?

Q # 4. What are the local initiatives for forest fire reducing activities?

Appendix III

1. Participants list of Consultation Meeting in the Department forests and Soil Conservation, Kathmandu

Date : 2014/04/8

Venue : Meeting Hall, Department of Forests and Soil Conservation (DoFSC), Kathmandu

1.	Mr. Yam Bahadur Thapa	DDG,Department of Forests and Soil
2.	Mr. Badri Kumar Karki	Section Head of Forest Management
3.	Mr. Ishoweri P. Paudyal	Section Head of Environment
4.	Mr. Rakesh Karna	Section Head of Protection
5.	Ms. Santamaya Shrestha	Section Head of Monitoring
6.	Mr. Sundar Sharma	Focal Person of Forest Fire Monitoring
7.	Mr. Indra P. Prashai	Section Head of Forest Utilization
8.	Mr. Rajkumar Rimal	Assistant Forest Officer, DoFSC
9.	Mr. Prakash Aryal	Assistant Forest Officer, DoFSC
10.	Mr. Santa Baral	Assistant Forest Officer, DoFSC

2. Participants list of Consultation Meeting under the DFO Office, Nawalparasi district

Date : 2014/04/12

Venue : Meeting hall of Divisional Forest Office, Nawalparasi

1.	Mr. Dhananjaya P. Paudel	DFO, Divisional Forest Office
2.	Mr. Promod Bhattarai	Assistant Forest Officer
3.	Mr. Mohan Kafle	Assistant Forest Officer
4.	Mr. Himlal Lamichhane	Assistant Forest Officer
5.	Mr. Keder P. Paudal	Assistant Forest Officer
6.	Mr. Man Bahadur Bhujel	Assistant Forest Officer
7.	Mr. Bhim Bahadur Paudel	Assistant Forest Officer
8.	Mr. Lal Bahadur P.Kurmi	Assistant Forest Officer
9.	Mr. Krishna Bdr. Devkota	Assistant Forest Officer
10.	Mr. Dhandapani Bhattarai	Assistant Forest Officer

3. The focus group discussion was held on 14/04/2016 on the Arunkhola Community Forest User Group (CFUG), Nayabelahani VDC, Ward No. 8, Nawalparasi

Name list of participants

1.	Mr. Chandra Bahadur Darahi	Chairperson
2.	Mr. Kashi Ram Mahoto	Member
3.	Ms. Bimala Sapkota	Member
4.	Mr. Harimaya Tamang	Member
5.	Mr. Ramkrishna Chaudhary	Member
6.	Ms. Pholmaya B.K	Member
7.	Mr. Chiranjibi Basnet	Member
8.	Mr. Prem Bahadur K.C	Member
9.	Mr. Indra Prasad Chaudhary	Member
10.	Mr. Eknath Kunwar	Member

4. The Focus Group Discussion (FGD) was held on 16/04/2014 on the Budhasanti Community Forest User Group, Sunwal VDC, Ward No.7, Nawalparasi

1.	Ms. Laxmi Bhatta	Chairperson
2.	Mr. Bishnu P. Bhandary	Member
3.	Mr. Triyuga Gharti	Member
4.	Mr. Sanjaya Gurung	Member
5.	Mr. Nirmal Mahato	Member
6.	Mr. Ramesh Paudel	Member
7.	Mr. Anirudra P. Yadav	Member
8.	Ms. Santa Kumari Chaudhary	Member
9.	Mr. Hera P. Kathayat	Member
10.	Mr. Ram Bahadur Thapa	Member

5. The Focus Group Discussion was held on 22/04/2014 on the DhaubadiCommunity Forest User Group, Dhaubadi VDC, Ward No.7, Nawalparasi

1.	Mr. Jiban Thanet	Chairperson
2.	Mr. Ram Bahadur Magar	Member
3.	Ms. Suntali Magar	Member
4.	Mr. Dinesh Paudel	Member
5.	Ms. Laxmi Khatri	Member
6.	Mr. Him Bahadur Ale	Member
7.	Mr. Nar Bahadur Tamang	Member
8.	Ms. Parbati Gole	Member
9.	Mr. Ranjita Magar	Member

6. The Focus Group Discussion was held on 24/04/2014 on the Jhahare Community Forest User Group, Rajar VDC, Ward No. 6, 8, Nawalparasi

1.	Mr. Agnidhar Sharma	Chairperson
2.	Mr. Balkrishna Devkota	Member
3.	Ms. Parbati Kumri Khatri	Member
4.	Ms. Usha Kumari Subedi	Member
5.	Ms. Sunita Chaudhary	Member
6.	Mr. Bikram Chaudhary	Member
7.	Ms. Kamala Paudel	Member
8.	Mr. Lok Bahadur Khatri	Member
9.	Mr. Tek Bahadur Magar	Member
10.	Mr. Nar Bahadur Bhatta	Member

7. The Focus Group Discussion was held on 30/04/2014 on the Forest Fire Watcher Group, Nayabelahani VDC, Ward No. 8, Nawalparasi

1.	Mr. Ghanshyam Rijal	Fire Fighter, Arunkhola CF
2.	Mr. Man Kumari K.C	Fire Fighter, Arunkhola CF
3.	Mrs. Lila Kumari Paudel	Fire Fighter, BudhaSanti CF
4.	Mrs. Hira Devi Magar	Fire Fighter, Joltepokhari CF
5.	Mr. Hom Bahadur Gurung	Fire Fighter, Joltepokhari CF
6.	Mr. Dinesh Thapa	Fire Fighter, BudhaSanti CF
7.	Mr. Rabindra Kumar G.C	Fire Fighter, Jhaharekhola CF
8.	Mr. Hira Prasad Katharya	Fire Fighter, Jhaharekhola CF
9.	Mr. Harisanker Parajuli	Fire Fighter, Kalika CF, Rajahar
10.	Mr. Gobinda Prasad Naur	Fire Fighter, Kalika CF, Rajahar

8. Participants list of Key Informant Interview

1.	Mr. Sundar Sharma	Focal Person, DoFSC, Kathmandu
2.	Mr. Sashman Shrestha	Former DG, DFRS, Kathmandu
3.	Mr. Vijaya Raj Subedi	Undersecretary, DoFSC
4.	Mr. Krishna P. Osti	Undersecretary, DoFSC
5.	Mr. Sambhu P. paudal	Faculty, Kathmandu Forestry College
6.	Mr. Triyugi Gharti	Foresters, DFO Nawalparasi
7.	Mr. Arun Kumar Mishra	Assistant Forest Officer, DFO Nawalparasi
8.	Mr. Kasiram Mahato	Leader of Bhedabari Community Forest
9.	Ms. Usha Kumari Subedi	Leader of Sundari Community Forest
10.	Ms. Sunita Chaudhary	Local Resource Person, Kumarwati Community Forest

9. Participants list of Consultation Meeting held on 2015/03/04 with Nepal Forester's Association, Kathmandu

1.	Mr. Kumod Shrestha	Voice-chairperson Nepal Forester's Association
2.	Mr. Subas Devekota	Member Nepal Forester's Association
3.	Mr. Shree Baral	Member Nepal Forester's Association
4.	Mr. Rajkumar Paudel	Member Nepal Forester's Association
5.	Mr. Rishiram Tripathi	Member Nepal Forester's Association
6.	Mr. Arun Sharma	Member Nepal Forester's Association
7.	Mr. Bishnu P. Aryal	Member Nepal Forester's Association
8.	Mr. Bhagat Manandar	Member Nepal Forester's Association
9.	Mr. Vijayaraj Paudel	Member Nepal Forester's Association
10.	Mr. Basant Shrestha	Member Nepal Forester's Association

Appendix IV: Materials used for biomass survey in the field

GPS used for boundary survey

Clinometer for measuring treeheight

Diameter tape for measuring DBH tree

Linear tape for measuring distance

Sickel, Hammur, Kuto and peg

Weighing machine

Appendix V: Photographs showing different field activities in the study area

Weighing leaf-litter, herbs and grasses

Delineation of burnt and non-burnt area

Measuring damage portion of pole

Measuring the pole size trees poles

Appendix VI: Wood density of plants species

SN	Local name	Scientific name	Specific wood density (g/cc)
1	Sal	*Shorea robusta*	0.88
2	Asna	*Terminalia tomentosa*	0.75 3
3	Botdhairo	*Lagerstroemia parviflora*	0.62 4
4	Khirro	*Sapium insigne*	0.4 5
5	Sindure	*Mallotus philipinensis*	0.64
6	Jamun	*Eugenia jambolana*	0.68
7	Banjhi	*Anogeisus latifolia*	0.78
8	Khayar	*Acacia catechu*	0.88
9	Amala	*Phyllanthus embelica*	0.76
10	Tantari	*Dillenia pantaguana*	0.53
11	Sissoo	*Dalbergia sissoo*	0.76
12	Karma	*Adina cordifolia*	0.59
13	Bhalayo	*Semecarpus onacardium*	0.34
14	Herro	*Terminalia chebula*	0.96
15	Piyari	*Buchanania latifolia*	0.450
16	Barro	*Terminalia bellarica*	0.76
17	Jamuno	*Syzygium cumini*	0.770
18	Bhalayo	*Semicarpous anacardium*	0.425

Appendix VII: Species parameters used to estimate sapling biomass (Tamrakar, 2000)

SN	Local name	Scientific name	Intercept (a)	Slope (b)
1	Khair	*Acacia catechu*	-4.30	0.434
2	Sissoo	*Delbergia sissoo*	-2.19	2.559
3	Sal	*Shorea robusta*	-2.608	2.996
4	Mixed species	*Eugelharlia* spp, *Sapium, Rush succedance, emblica, syzium* species	-0.280	1.510

Appendix VIII: Moisture Content of Leaf-litter, Herbs and Grasses (LHG)

Forest types	Name of sample forest	Moisture content (%)		
		Leaf-liter	Herbs	Grass
Lower Tropical Sal-mixed Broad-leaved Forest	Budhasanti Community Forest	10.61	31.7	15.61
Hill Sal Forest	Arunkhola Community Forest	11.55	28.55	18.55
Hill Sal Forest	Daubadi Community Forest	13.7	31.21	2
Riverine Forest	Jhahare Community Forest	12.42	22.32	14.24

Appendix IX: Forest fire occurrence and burnt area recorded in the climatic factor (temperature and precipitation)

Forest fire incidence and burnt area recorded in the maximum and minimum temperature of active fire season and annual precipitation during the period from 2001-2017.

Year	Temperature maximum, minimum & fire incidence burnt area				Annual precipitation & fire incidence, burnt area		
	Temp (max)	Temp (mini)	Fire incidence (no.)	Burnt area (ha)	Precipitation mm	Fire incidence (no.)	Burnt area (ha)
2001	30.22	18.63	78	5981.69	2870.1	78	5981.69
2002	30.62	19.46	5	0	2661.4	5	0
2003	29.29	18.42	106	967.54	3263.4	106	967.54
2004	30.73	18.05	132	9790.19	2121.6	132	9790.19
2005	32.53	19.30	116	1797.17	2407.8	116	1797.17
2006	30.16	18.36	107	1733.33	2369.6	107	1733.33
2007	31.24	17.60	80	275.05	3027.3	80	275.05
2008	30.97	17.21	121	4720.83	3103.3	121	4720.83
2009	29.78	18.50	143	3678.78	2612.6	143	3678.78
2010	32.50	17.18	155	9193.88	2708.3	155	9193.88
2011	29.95	17.44	66	719.56	2125.6	66	719.56
2012	28.26	16.10	110	402.11	3321.2	110	402.11
2013	30.83	15.07	85	402.11	2654.7	85	402.11
2014	32.21	18.07	78	1397.06	1786.5	78	1397.06
2015	32.21	18.07	8	0	2300.88	8	0
2016	33.34	18.71	124	9454.79	2184.82	124	9454.79
2017	33.29	19.50	28	3060.92	2350.38	28	3060.92
Total			1542	53575		1542	53575

Appendix X: Forest fire occurrence and burnt area recorded in the forest types (2001-2017)

Year	Number of fire incidence			Forest burnt area (ha)		
	ltsmf	hsf	rf	ltsmf	hsf	rf
2001	32	46	0	959	4742	0
2002	7	4	2	205	104	4
2003	17	68	1	460	502	3
2004	48	81	3	2797	5958	5.2
2005	22	87	7	381	1353	12
2006	28	73	6	248.9	1278	9
2007	24	56	0	63	212	0
2008	29	63	2	2129	2542	10
2009	47	96	0	1089	2897	0
2010	52	96	7	1875	7068	12.1
2011	24	42	0	402	317	0
2012	45	48	2	148	254	3
2013	40	49	0	148	254	0
2014	37	44	1	296	1201	2
2015	3	2	0	50	30	0
2016	57	83	8	1887	7738	21
2017	21	32	0	1564	2341	0
Total	533	970	39	14701.9	38791	81.3
Annual	31	57	2	864.82	2281.82	4.8

Appendix XI: Forest fire drivers' identification and their prioritization

SN	Name of drivers	Number of score	Score (%)
1	Forest distance from road	4	11.6
2	Precipitation	3.6	10.5
3	Elevation	3.2	9.3
4	Forest distance from Settlement	3.0	8.7
5	Forest fuel	3.0	8.7
6	Temperature	2.8	8.1
7	Slope	2.6	7.6
8	Aspect	2.4	7.0
9	Grass cutter	1.4	4.1
10	Humidity	1.2	3.5
11	Campfire	1.2	3.5
12	Cigarette butts	1.2	3.5
13	Burning matches	1.0	2.9
14	Fuel-wood collector	0.9	2.3
15	Vehicles' spark	0.8	2.3
16	NTFPs collector	0.8	2.3
17	Trash fire	0.6	1.7
18	Wildlife poachers	0.4	1.2
19	Smoking-beehives	0.2	0.6
20	Lighting	0.2	0.6
	Total	34.4	100.0

Appendix XII: Forest fire occurrence and burnt area recorded in the topographic factor (aspect, slope, elevation) during the period from 2001 to 2017

Forest fire occurrence and burnt area record in different aspect

Year	Forest fire incidence				Forest burnt area (ha)			
	N	E	S	W	N	E	S	W
2001	15	22	22	19	1455.5	1105	2114	1057
2002	0	2	0	3	0	11	0	0
2003	17	25	37	27	205.8	169	529	64
2004	22	34	34	31	1589.8	1587	3322	3195
2005	23	34	21	38	486.6	402	592	317
2006	17	30	34	26	592.1	338	465	338
2007	18	25	19	16	21.2	85	148	21
2008	22	31	36	21	909.6	1121	1227	1523
2009	23	45	51	24	846.4	750	1095	951
2010	23	44	60	28	1439.1	1814	3025	2516
2011	13	17	19	17	126.9	64	360	169
2012	13	36	25	28	148.1	21	106	127
2013	14	28	30	13	105.4	21	135	127
2014	6	23	30	19	275.1	466	137	529
2015	1	2	2	3	0	0	23	7
2016	20	38	43	23	1755.5	2069	3216	2115
2017	12	15	18	15	783.7	805	1080	1377
Total	259	451	481	351	10740.8	10828	17574	14433
Annual	15	27	28	21	631.81	636.94	1033.76	849

Forest fire occurrence and burnt area record in different slope

Year	Forest fire incidence			Forest burnt area		
	0-15%	**15-30%**	**>30%**	**0-15%**	**15-30%**	**>30%**
2001	10	11	51	1712.4	4734.3	465
2002	3	0	2	33	0	21
2003	15	24	46	205.8	169.2	529.1
2004	43	30	59	2113.8	4652	2050.8
2005	17	23	79	444.2	1099.2	253.8
2006	14	17	76	338.4	1331.5	63.5
2007	19	15	46	21.2	84.6	148.1
2008	39	17	65	1608	2517	655.8
2009	40	25	78	1057.4	2431.1	190.2
2010	56	22	77	2933.2	4218.4	1042.3
2011	19	16	31	105.8	465.6	148.1
2012	53	15	42	296.3	42.3	63.5
2013	41	14	30	296.3	42.3	63.5
2014	35	13	30	698.4	487.1	211.6
2015	4	1	3	35	0	21
2016	55	20	49	3765.7	5033.4	655.7
2017	32	17	3	1510.9	1916.2	592.8
Total	495	280	767	17175.8	29224.2	7175.8
Annual	29	16	45	1010.34	1719.0706	422.10588

Forest fire occurrence and burnt area record in different elevation

Year	Forest fire incidence			Forest burnt area (ha)		
	<500	**500-1000**	**1300-1000**	**<500**	**500-1000**	**1300-1000**
2001	23	31	24	2368.2	2070.1	1263.3
2002	4	1	0	11	0	0
2003	31	51	11	544.9	253.6	169
2004	75	50	11	8923	1401.6	105.6
2005	34	64	27	592.4	1056.9	147.9
2006	36	60	20	401.7	930.4	401.3
2007	40	35	11	169.3	84.6	21.1
2008	53	36	10	3745.2	655.3	380.2
2009	71	55	21	1544.1	1669.8	464.8
2010	82	59	19	3318.9	3262.1	1209.9
2011	34	26	11	677.2	42.4	0
2012	42	24	5	359.8	42.3	23
2013	62	21	3	359.8	42.3	0
2014	69	14	3	1036.9	360.1	51
2015	4	1	3	21.7	37	0
2016	58	20	49	6114.5	4650.8	84.6
2017	31	14	3	762.7	1049.8	692.7
Total	749	562	231	30951.3	17609.1	5014.4
Annual	44	33	14	1820.66	1035.83	294.96

Appendix XIII: Forest fire occurrence and burnt area recorded in the anthropogenic factors (forest distance from road and settlement) during the period from 2001 to 2017

Forest fire occurrence and burnt area recoded in the forest distance from road

Year	Numbers of fire incidence			Forest burnt area (ha)		
	<500 (m)	500-1000 (m)	>1000 (m)	<500 (m)	500-1000 (m)	>1000 (m)
2001	56	16	8	5812	688	212
2002	3	0	2	23	0	17
2003	76	13	3	641	233	121
2004	92	28	14	7215	532	335
2005	98	16	5	1289	254	254
2006	82	23	5	1247	296	190
2007	61	12	7	123	79	13
2008	69	21	11	3608	719	360
2009	97	34	13	3169	508	42
2010	100	39	19	7915	1516	508
2011	43	14	9	529	233	106
2012	51	23	15	296	43	64
2013	46	21	18	296	42	64
2014	45	26	9	1352	85	106
2015	8	0	0	0	0	0
2016	85	28	17	7487	740	952
2017	32	18	11	2565	339	358
Total	1044	332	166	43567	6307	3702
Annual	61	20	10	2562.76	371.00	217.76

Forest fire occurrence and burnt area recoded in the forest distance from settlement

Year	Forest fire incidence			Forest burnt area (ha)		
	<500 m	500-1000 m	>1000 m	<500 m	500-1000 m	>1000 m
2001	13	36	29	3904	1939	1055
2002	3	2	0	11	8	0
2003	37	33	34	580	216	171
2004	39	37	49	4208	1545	2301
2005	25	51	42	761	486	508
2006	29	37	36	698	507	528
2007	22	36	22	25	148	106
2008	31	35	36	979	1288	2213
2009	47	45	51	1670	1142	762
2010	39	51	65	3295	2529	3369
2011	16	21	29	95	248	377
2012	16	24	45	85	254	106
2013	23	33	29	93	254	106
2014	12	29	37	237	264	744
2015	1	3	4	7	25	254
2016	31	54	39	5048	2432	1979
2017	37	26	21	1529	1032	1455
Total	421	553	568	23225	14317	16034
Annual	25	32.5	33.4	1366.18	842.176	943.176

Appendix XIV: Photographs of forest fire damage in the different forest types in the study area

Surface fire in the Lower Tropical Mixed Broad-leaved Forest

Surface fire in the Hill Sal Forest

Surface fire in the Lower Tropical Mixed Broad-leaved Forest

Surface fire in the Hill Sal Forest

Appendix XV: Photographs showing the loss and damage of forest resources due to forest fire

Damage of ground vegetation (LHG)

Damage of sapling and regeneration

Damage of pole size forest

Burning of dead tree in the forest

Appendix XVI: Participation in International Conference


Nepal Academy of Science and Technology

CERTIFICATE

Awarded to

Krishna Bahadur Bhujel

for active participation/paper presentation/poster presentation

in

THE 7th NATIONAL CONFERENCE ON SCIENCE AND TECHNOLOGY

SCIENCE, TECHNOLOGY AND INNOVATION FOR NEPAL'S GRADUATION TO DEVELOPING COUNTRY STATUS

March 29-31, 2016

Kathmandu, Nepal

Mrs. Ramila Shrestha Raut, Chief, Promotion Division

Dr. Buddhi Ratna Khadge, Secretary

Prof. Dr. Jiba Raj Pokharel, Vice-Chancellor


USAID

Certificate of Participation

This is to certify that Prof./Dr./Mr./Ms.

Krishna Bahadur Bhujel

has presented paper/poster/attended

the International Conference on Biodiversity, Climate Change Assessment and Impacts on Livelihood

at Kathmandu on January 10-12, 2017.

Dr. Bishwa Nath Oli, Secretary, Ministry of Population and Environment

Dr. Nir Krakauer, Co-Chair, Conference Organizing Committee, PI-USAID-IPM-IL Biodiversity Project

Prof. Naba R Devkota, Director of Research, Agriculture and Forestry University

Prof. Mohan Siwakoti, Secretary, Conference Organizing Committee, Head, Central Dept. of Botany, TU

Prof. Pramod K Jha, Chair, Conference Organizing Committee, Nepal Coordinator & Co-PI USAID-IPM-IL Biodiversity Project


Certificate of Attendance
Krishna Bahadur Bhujel
International Conference on Wild Harvests, Governance and Livelihoods in Asia


USAID
Certificate of Participation
This is to certify that Prof./Dr./Mr./Ms.
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Prof. Naba R Devkota
Prof. Mohan Siwakoti
Prof. Pramod K Jha

ESP

भारतीय वन्यजीव संस्थान
Wildlife Institute of India

Certificate of Participation

Awarded to

Krishna Bahadur, Nepal

for Oral Presentation at

2018 Ecosystem Services Partnership (ESP) Asia Conference:

'Communicating and Engaging Ecosystem Services

in Policy and Practice in Asia'

9th to 12th October, 2018

Wildlife Institute of India, Dehradun

Dr. Rudolf de Groot	Dr. V. B. Mathur	Dr. Namue Lee
Chair, Ecosystem Services Partnership	*Director, Wildlife Institute of India & UNESCO C2C*	*Director, ESP Asia Regional Office*

Appendix XVII: Scientific paper published based on the research

Bhujel, K.B., Maskey, R., Gautam, A.P., Mandal, R.A. (2017a). Effect of climatic variables on fire incidence and burnt area in the tropical forests in Nepal. *e-planet* **15** (1):21-28.

Bhujel, K.B., Maskey, R., Gautam, A.P. (2017b). Wildfire Dynamics in Nepal from 2000-2016. *Nepal Journal of Environmental Science*, 5, 1-8. ISSN2350-8647 (print) 2542-2901 (Online).

Bhujel, K.B., Maskey, R., Gautam, A.P., Mandal, R.A. (2018a). Wildfire Dynamics and Occasional Precipitation during Active Fire Season in Tropical Loeland of Nepal. *Environment and Natural Resources Journal* 16(1):1-8.

Bhujel, K.B., Maskey, R., Gautam, A.P., Mandal, R.A. (2018b). Wildfire Dynamics and Its Effects on the Forest Resources and Public Property in Nepal. *Journal of Institute of Science and Technology*, 23:61-68. ISSN: 2469-9062 (print), 2467-9240 (Online).

e-planet **15** (1): 19-26 (June 2017)

Effect of climatic variables on fire incidence and burnt area in tropical forests in Nepal

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ABSTRACT

This research was objectively done to correlate the climatic variables with the number of wildfire incidence and burnt area in Nawalparasi, Nepal. MODIS satellite data was used to detect the fire incidence and burnt areas. Climatic (temperature and humidity) data for 2000-2014 periods were obtained from Government of Nepal. The burnt areas of each year were clipped using Arc GIS to calculate the fire affected areas and number of incidences. Meanwhile, the correlation was evaluated to determine the relationship of climatic variables with the fire incidence and burnt area. The analysis showed that temperature and humidity of the study area varied throughout the active fire season (March to May). R^2 values were 0.0123 and 0.0260 of temperature with number of fire occurrence and brunt area respectively. R^2 was same nearly 0.0288 of the correlation of humidity with fire incidence and burnt area. The regression models were tested applying t-test ($p \leq 0.05$) for humidity with fire incidence and burnt area. The results showed that there was a clear relationship between wildfire and climatic factors, especially the humidity. The findings can be useful to establish baseline information for forest fire management in Nepal and other developing countries with similar ecological contexts.

Key words: Burnt area, climatic variables, fire occurrence, MODIS

INTRODUCTION

Wildfires are integral component of the earth system, which play key role in regulating vegetation structure and ecosystem functions (Balling, Meyer and Wells 1992). An increase in the number of wildfires and burnt area has been reported during the last decades in many parts of the world (Stocks et al., 1998) and (Flannigan, Stocks and Weber 2003; Brown JT 2004) . Fuel load inside forest governs the occurrence of fire along with the dryness of the fuel which indirectly determines the availability of fuel moisture (Chuvieco et al., 2004). Fire regimes are controlled by a very wide array of factors (Krebs et al., 2010). There is relation between patterns of fire and the climatic variables (Debnath et al., 2012)

Climate variables like temperature and humidity are two crucial drivers of fire activities. High temperatures and low humidity can cause fuel drying and hence an increase in fire occurrence. Climatic conditions affect the fuel accumulation and moisture, thus having an effect on the probability of a fire to occur as well as on its spread over the landscape (Syphard et al., 2008 and Vilar et al., 2010). The climatic factors have been emerged as evidence for wildfires, especially large wildfires (Piñol, Terradas and Lloret, 1998; Gillett, 2004 and Swetnam, 2006).

Global temperature has increased by ~0.2^0C per decade over the last three decades (IPCC, 2007). Nepal also experiences increase in mean annual temperature by 0.04°C and 0.01°C in maximum and minimum respectively during 1971-2012. The highest temperature was recorded in the Terai and Siwalik regions and the lowest in the High Himalaya region (Government of Nepal 2015). Nepal has experienced anomalous wildfire events in recent years including some transboundary fires (Government of Nepal 2010). Despite the fact that wildfire has been a major environmental problem, there is no systematic and complete record of the wildfire occurrence and their effects in Nepal (Bajracharya, 2001). In this context, the paper attempts to answer a key question: does the fire incidence and burnt area respond to climatic factors? Hence the study was carried out to identify correlation of climatic variables with the number of wildfire incidences and burnt area in Nawalparasi district of Nepal during period of 2000-2014.

MATERIALS AND METHODS

Study area

The study district is located in the Lumbini Zone in the Western Development Region of Nepal and lies within latitude 27°21' to 27°47' and longitude 83°36' to 84°25' covering an area of 2162 sq.km, The elevation ranges from 91m to 1936m above the mean sea level. About 55 % (122, 365 ha.) of district land is under forest. *Shorea robusta* and Terai hard wood, Terai Hardwood forest, Riverine forest *Dalbergia sissoo* and *Acacia catechu* are the main forest types found in the district. *Shorea robusta* is the dominant species in 94% of the forest areas. Approximately 16% of the total area comprises mountain region and the remaining land include Siwalik (fragile small hills), Terai (flat lands) and Inner Terai (valleys in the Siwalik- foothills of the mountain) regions. The latter two regions have a gentle slope up to 15^0, while the Mahabharata (lower elevation hill) and Siwalik range bear steep slope 15-50^0. Most (61.7%) of the forests are located in the Siwalik. The Terai and hill regions have 22.45% and 15.98% forest covers, respectively. About, 6% of the forests have been handed over to local communities as community forest. The east-west national high way passes through the central part of the district. The study area has divided into three physiographical region such as Terai, Siwalik and hill where covers.

The study area is vulnerable to forest fire particularly during the summer months from March to April due to high temperature and very dry condition. According to District Forest Office (DFO), the occurrence of forest fire and its adverse effects on the forest services have increased in recent years; resulting in loss of forest products and adverse effect on the local economy.

Data sources and collection methods

Two types of data were collected and used in the research, including the Moderate Resolution Imaging Specto-radiometer (MODIS) of Terra and Aqua satellites observation data and the climatic data. The satellite data was downloaded free of cost from MODIS satellite image while climatic data for the period of 2000-2014 were acquired from the Department of Hydrology and Meteorology (DHM) Nepal. The active fire points are the past actual fire occurrences that have occurred in the area as recorded by MODIS of Terra and Aqua satellites. The past fire occurrences data, which provides the location and date of fire ignitions, were obtained from MODIS active fire products (version 5.1). Those point data in the form of shape files were then further analyzed in Arc Map 10.1. Point count by polygon method was used to identify the number of fire occurrences within the study area.

The burnt area related data was obtained from MODIS in the form of TIFF format containing burnt area pixels along with the burnt date information. The monthly level 3 gridded burnt area product (MCD45A1) of Terra and Aqua satellites were downloaded from the ftp server (ftp: //bal.geog.umd.edu/Collections5/TIFF/Win18/) for 15 years (2000 – 2014). Burnt area pixels within study district of Nepal were then extracted from the TIFF format using clip function processed in Arc Map 10.1. Again clip function was applied to extract district boundary shape file of study area. Meanwhile, the climate data (temperature and relative humidity) of the study area were collected as daily basis annual data from the Department of Hydrology and Meteorology for the period of 2000-2014. It was used to identify the climatic characteristics of study area in the spring season (March, April and May).

Data analysis

The data on fire incidences, burnt area and climatic variables over the 15 years (2000-2014) was analyzed using Microsoft Excel and SPSS 20 to find out trends, condition and its correlation between the wildfire occurrence, burnt area and climatic factors (temperature and humidity).The method adopted in data analysis is described in detail in the following sections.

Analysis of historical pattern of wildfire and climatic condition

The collected daily basis data of temperature and relative humidity was converted in to annual form by using the Microsoft Excel program. The mean, standard error, standard deviation, maximum and minimum of months of May, April and March over the 15 years period were analyzed by using the SPSS (version 20). The temporal data of climatic factors was graphically plotted by using Microsoft Excel tool. It helped explore the information of behavior of the climatic factors within the given period. The clip function was applied to extract district boundary shape file of study district. The number of wildfire occurrence and burnt area were extracted from the attribute tables of shape files. The extracted data was graphically analyzed by using the Microsoft Excel and SPSS (version 20).

Analysis of correlation between fire occurrence, burnt area and climatic variable

The relationship between the number of fires, burnt area against the climatic variable (temperature and relative humidity) of spring season (March, April and May months) was analyzed in SPSS 20 version. The linear regression was carried out to find the relationship between wildfire occurrence, burnt area and climatic variables. The mean, standard error, standard deviation, maximum and minimum range of temperature, humidity, number of fire occurrence and burnt area were analyzed by using the descriptive statistical tool. The value of Pearson correlation (r) and R^2 values were calculated by using liner regression and t-test at 5% level of significance to find out the relationship between mean temperature and relative humidity against the no. of fire incidence, burnt area of the study area.

RESULTS AND DISCUSSION

Climatic condition (Mean temperature and humidity)

The March, April and May months comprise an active season in the study area. The mean temperature of March, April and May were 23.13°C, 28.80°C and 30.73°C, respectively. The (Fig.1a) showed the highest mean temperature in May, while it was lowest in March. Meanwhile, relative humidity were recorded

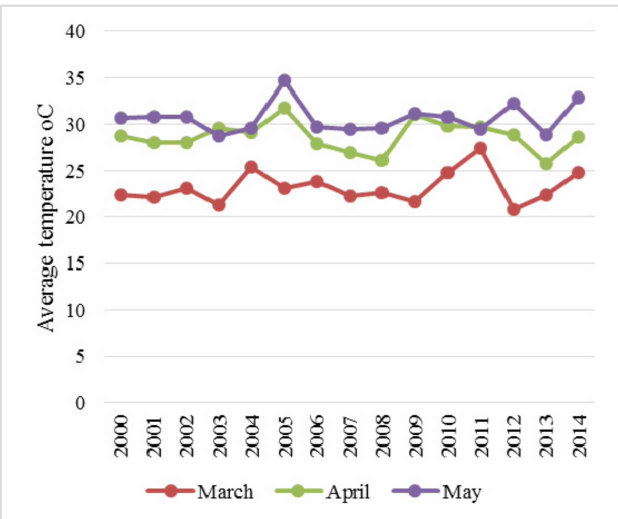

Fig.1a. Mean temperature condition

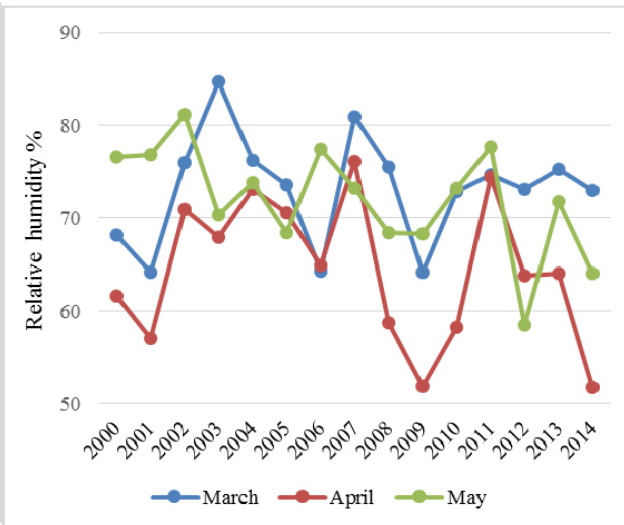

Fig. 1b. Average relative humidity in %

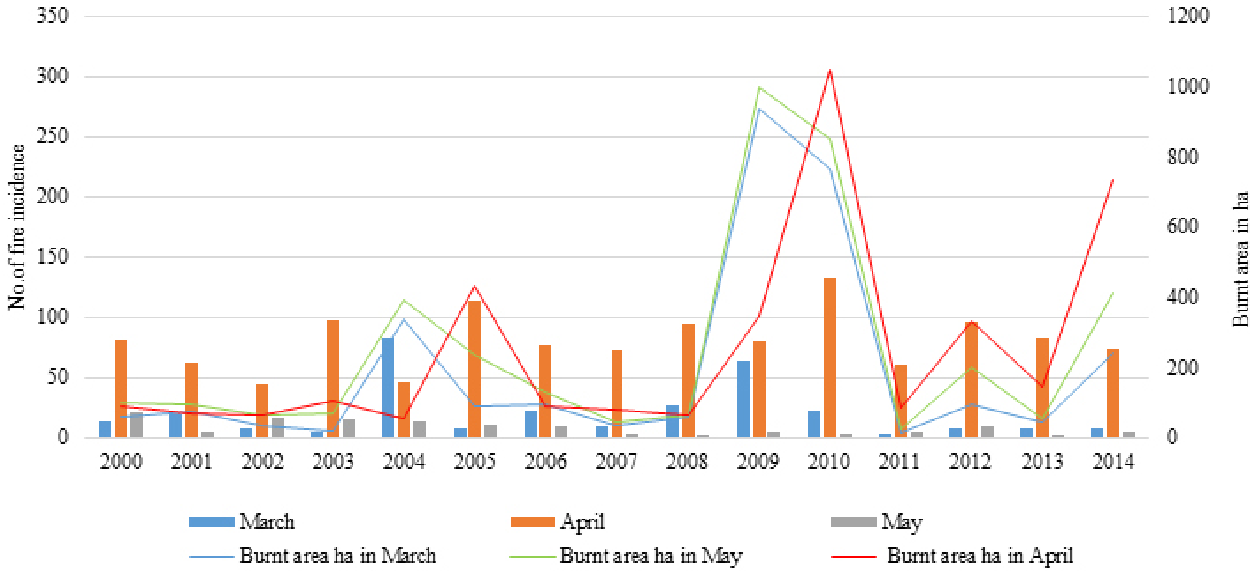

Fig. 2. Spatial and temporal no. fire incidence, burnt area

73.13, 64.40 and 71.93% in of March, April and May respectively (Fig.1b). The lowest relative humidity was recorded 52 % in 2009 and 2014 years, which was followed by 2001 in April with 57%. The relative humidity was the highest in March and lowest in April. The overall condition of both climatic variables was found varying over the 15 years period in the study area.

Spatial and temporal status of fire incidence and burnt area

Trends of spatial and temporal fire incidence and burnt area of March, April and May months of 15 years showed that the number of fire incidence was the highest in April in comparison to March and May and same result was recorded for burnt area as well (Fig. 2).

The highest number of wildfire incidences noticed in April of 2003, 2005, 2009, 2010 and 2012 where other March and May months indicated lowest. The highest record of burnt areas were found in year 2005, 2009, 2010, 2012 and 2014. The 1, 472 wildfire incidences and 4615.28 hectares forest burnt were recorded in the active fire season over the 15 years which constitutes 82.5% of total annual wildfire incidence and burnt area. The anomalous wildfire incidences were found during the active fire season (Fig. 2).

Statistics of temperature, humidity, number of fire occurrence and burnt area

The statistical result showed variation on the temperature, humidity, wildfire occurrence and burnt area of forest, resulting in instability of these variables. The maximum temperature (30.7^{o}C) and humidity (73.1%) were recorded in May and March months while the highest mean number of fire occurrence (i.e. 81) and largest burnt area (248.5 hectares) occurred in April. It was indicated that April was higher affected month than other during the active fire season (Table 1).

Relationship of climatic variables with wildfire events

The regression fit line between temperature and forest fire incidence is presented in the (Fig.3a). This showed that the model y = 1.1684x + 4.134 whereas y denotes number of fire occurrence as dependent variable and x stands as independent variable for temperature. The R^2 = 0.0123 value showed positive relation between temperature and numbers of wildfire

Table 1. Variation in temperature, humdity, fire incidence and burnt area

Variables	Months	Mean	Standard Error	Standard Deviation	Maximum	Minimum
Temperature (Degree Celsius)	March	23.1	0.44	1.72	27.00	21.00
	April	28.8	0.43	1.69	32.00	26.00
	May	30.7	0.43	1.66	35.00	29.00
Humidity (%)	March	73.1	1.56	6.04	85.00	64.00
	April	64.4	1.99	7.74	76.00	52.00
	May	71.9	1.51	5.87	81.00	59.00
No. of fire	March	20	5.92	22.94	83.00	3.00
	April	81	6.18	23.94	133.00	44.00
	May	8	1.51	5.87	21.00	2.00
Burnt area ha	March	56.5	21.36	82.74	274.00	4.00
	April	248.5	75.68	293.13	1045.00	55.00
	May	16.3	3.79	14.68	50.00	1.00

occurrence. The p values ($p \geq 0.05$) showed the temperature was insignificantly correlated with the incidences of wildfires.

The result of relationship between temperature and burnt area is presented in the (Fig. 3b). It showed the equation y = 8.5231 x - 122.81 whereas y denotes burnt area as dependent variable and x stands as independent variable for temperature.

The R^2 value of regression fit line between temperature and burnt area was 0.022 which showed positive relationship between temperature and numbers of fire occurrence. The value ($p > 0.05$) showed insignificant relationship between temperature and forest burnt area.

The Fig. 4a showed equation y= -2.5423x + 214.03 whereas y denotes number of fire occurrence as dependent variable and x stands as independent variable for humidity. The regression fit line with humidity and number of fire occurrence indicated negative relationship with R^2= 0.2621.The value ($P<0.05$) showed the correlation exists significantly between humidity and fire incidences.

The Fig. 4b showed equation y= -14.84x + 1149.3 whereas y denotes burnt area as dependent

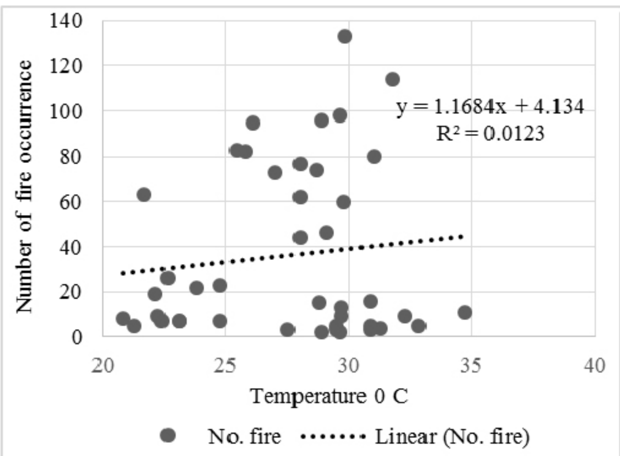

Fig. 3a. Relationship between temperature and number of fire occurrence

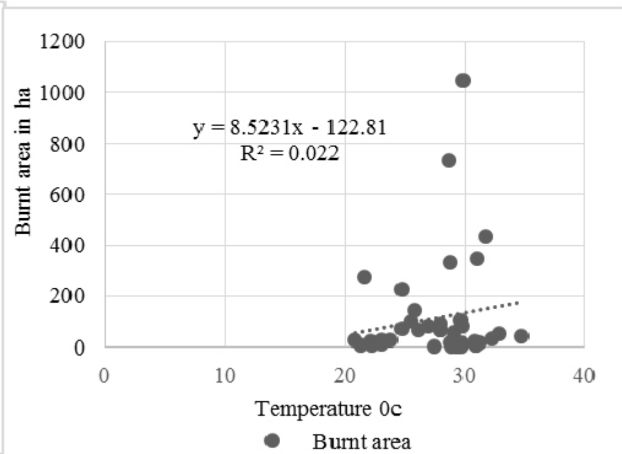

Fig.3b. Relationship between temperature and forest burnt area

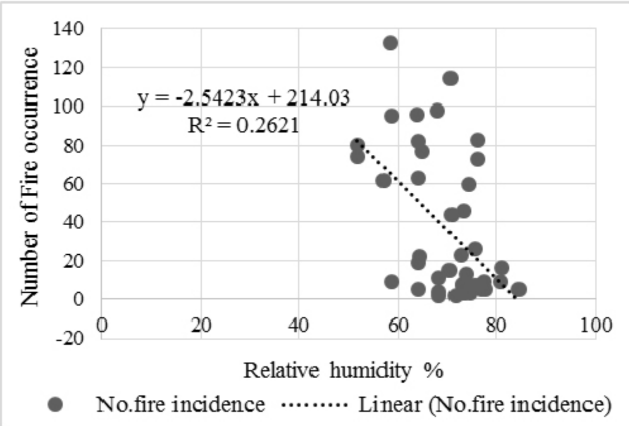

Fig. 4a. Relationship between humidity and numbers of wildfire occurrence

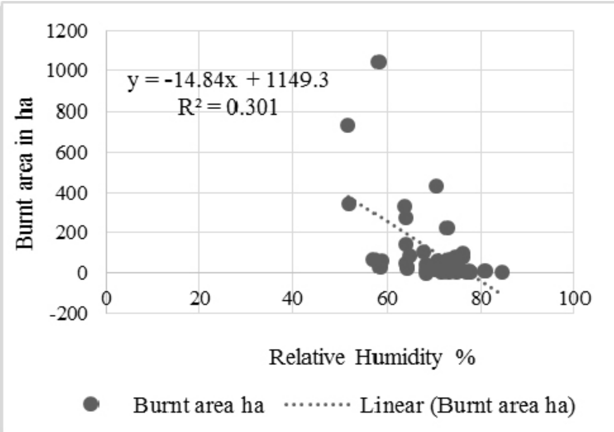

Fig. 4b. Relationship between humidity and burnt area

variable and x stands as independent variable for humidity. The regression fit line between humidity and burnt area was negative relationship having R^2 (0.301). Likewise, the value $p<0.05$ indicated the significant relationship.

DISCUSSION

These results showed the variation in the mean temperature which indicate a slight but definite warming trend in the mean temperature in the active fire season (pre-monsoon season). The study report of climate and climatic variation over Nepal (Government of Nepal, 2015) also showed the increasing trends of mean temperature between the periods of 1971-2012 in the entire country which was similar to this research findings. The (IPCC 2007) report also showed that future global temperature will be warmer than current levels, resulting an increase in the drought areas creating favorable environment to wildfire activity which statement supported to this research. Similarly temperature change is also found in most parts of the China (Tang et al., 2010). Spatial and temporal analysis of rainfall and temperature trend of India study report showed the temperature fluctuations and increase significantly (Mondal, Khare and Kundu, 2015). Both results corroborate with our research findings.

The relative humidity also found to vary during March, April and May months. The lowest humidity (64.40%) was found in April month. The research finding was consistent with Alexandrose Dimitrakopoulos 2011, whose result showed the large fire incidents occurred during the heat waves (higher air temperature and lowest humidity). It was supported by Urbieta et al., 2015 result which indicated low humidity in April was the indication of favorable fuel as well as the hot temperature being suitable for ignition and expansion of the fire.

The number of fire incidences and burnt areas increased annually. The April month was found with highest number of fire incidence and burnt area during the fire active season. The finding was consistent with study of Kiran Chand et al. (2006) which showed higher numbers of forest fires incidence occurred in the mixed deciduous forests in central Indian range during the March– April. The result of the study undertaken by Bowman et al. (2017) indicated that the extreme wildfire events were globally distributed across all flammable biomes which supported this result.

The present research showed the positive relationship between number of fire occurrence and burnt area with the mean temperature. Meanwhile, it depicted negative relationship between humidity and number of fire occurrence as well as burnt area. The relationship coexists between wildfire and climatic factors, especially with the humidity. A research done by Khanal, S., (2015), showed that there was strong relationship of climatic variables with fire activity in Nepal. Another research by Srivastava (2013) showed that the positive correlation exist between incidences of fire with temperature in tropical dry deciduous forest of India. Similarly, other research done by authors Swetnam (2006) and Kodandapani (2004), emphasized that the number of wildfires and burnt areas were increased in different terrestrial ecosystems across the globe. It can be said that three months like March, April and May are active fire season.

CONCLUSION

The climatic variables particularly temperature and humidity are the key factors affecting forest fire incidence and burnt area. The higher mean temperature and the lowest humidity cause increased long spell of dryness leading to low moisture in the combustible material which favor increase in fire incidents. The month of April showed the highest numbers of fire incidence and burnt area, which was followed by March. The relationship coexists between wildfire and climatic factors, especially with the humidity. The findings are expected to be useful for managing forest fires, with similar ecological contexts. Further research in this context is necessary to establish baseline information for wildfire management planners, early fire warning system and sustainable forest management.

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Research Article

Wildfire Dynamics in Nepal from 2000-2016

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Abstract

Increasing trends of wildfire in recent year has become a serious concern across the world. However, in the Nepalese context, there seem limited studies carried out in connection to wildfires. Thus, the present research was objectively carried out to find out the trends, compare the wildfire incidence, burnt area, burning days and density of wildfire in the period before 2016 (2000-2015) and 2016. For the purpose, the Moderate Resolution Imaging Spector-Radiometer (MODIS) satellite images of Nepal were archived and literatures related to wildfires were collected from various sources. The burnt areas were calculated and wildfire incidences were counted in the image using ArcGIS. The wildfire events of before and during 2016 were compared by using excel program. The result showed wildfire incidence and burnt area are in increasing trends over the 17 years. The wildfire incidences were higher (around 33%) in 2016 in compared to the annual average incidences from 2000 to 2015. Similarly, there seems 42% more burnt areas in 2016 as compared to period from 2000 to 2015. Moreover, there seem 38 average annual wildfire days during the period from 2000-2015; however 40 wildfire days were recorded in 2016 adding two more days. The pre-monsoon period was found highly prone to wildfire incidence than the other seasons. The wildfire density showed around 0.09 incidence and 3.4 hectares burnt area per square km in 2016 which was only 0.03 incidences with 1.4 ha burnt area per km^2 during 2000-2015. The highest density of wildfire was recorded to be nearly 0.16 incidences with 6.4 ha burnt area per km^2 in 2016 in Tarai region. The findings will be helpful tool to wildfire ecology, wildfire managers and policy makers.

Key words: Burnt area, wildfire densities, wildfires day, wildfire incidence

Introduction

Wildfire is a major environmental and ecological issue in the world. It was recognized as a global serious environmental process which has been influenced by the atmosphere and biosphere (Bowman et al., 2009). Globally, 350 MHa areas burned annually (Giglio et al., 2013). Around 0.4% of the global land surface is reportedly burned every year which covers 30 - 46 million km^2 (Randerson et al., 2012). Over 80% of the global area burned is grassland and savannahs, primarily in Africa and Australia, but also in South Asia and South America, while the remaining 20% wildfire incidence was recorded in forest and shrub-dominated regions (Flannigan et al., 2009). Wildfire magnitude is influenced by the distribution of forest resources (fuels), topography and favorable environmental conditions (climate, and day-to-day weather conditions) (Parisien & Moritz, 2009). Fuels provide the raw material, while the climate variables regulate fire occurrence patterns (Zhao & Running, 2010). The carelessness, unsustainable management of the forests and variation in climatic variables are the main causes of fire incidence in Asia (Streets et al., 2003).

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Global temperatures have increased by ~ 0.2^{o}C per decade over the last thirty years (Hansen et al., 2010; Hartmann et al., 2013). Kothawale et al. (2010) have reported that the mean temperature during the pre-monsoon season (March–May) was the hottest in South Asian region. The annual air surface temperature trends are increasing in India (Rohini et al., 2016). The extreme severe heat waves (> 40^{o}C) events were recorded on 11 April and 21 May in 2016 which is the rare events in nature before (Singh et al., 2017). In Nepal, changes in temperature and precipitation are the reliable evidences of increasing fire incidences (Negi et al., 2012). The decreasing pattern of precipitation and long spell of rain off days are the evidences of severe wildfire in coming days (Wang et al., 2013).

Nepal has been experiencing irregular wildfire events in recent years during the dry season from November to June every year. The evidence showed that number of wildfire is increasing in Nepal, and affecting natural vegetation (Parajuli et al., 2015). The wildfire incidence was remarkably higher in 2016 (Jenner, 2017).

The study of actual scenario of wildfire activities during 2000-2015 and in 2016 in Nepalese context is still scanty. In this context, several questions are raised regarding the noticeable wildfire events in 2016, some important questions are: whether there is large number of wildfire incidences in 2016 compared to 2000-2015, what is the pattern of wildfire incidences in the period between 2000 and 2016? Thus, the present research has tried to answer these questions, as the research was objectively carried out to compare the wildfire incidence, burnt area, burning days and density of wildfire from 2000 to 2015 and during 2016.

Materials and Methods

Study area

The study area covers whole geographical area of Nepal, which is situated between latitude 26⁰22'N and 30⁰27'N, and longitude 80⁰40'E and 88⁰12'E with area coverage 147 181 km^2. Nepal is divided into five physiographic zones like High Himalayan, High Mountain, Middle Mountain, Siwalik and Tarai (Fig.1). The High Himalaya region includes the highest Himalayan massifs. The High Mountain region is characterized by the rugged landscape and very steep slopes. The Middle Mountains region lies north of Siwalik along the southern flanks of the High Mountain.

Siwalik region is the youngest mountain range, across the southern part of Nepal which is embedded with the just north of Tarai. The Tarai consists of flattened and gentle slope having high fertile land. Nepal mostly exhibits mountainous terrain with elevation ranging from 58 m to 8848 m amsl at Mount Everest. Nepal is home to 35 forest types, 75 vegetation types and 118 ecosystems, along the four global biodiversity hotspots (Chettri et al., 2008). However, these ecosystems have been facing severe challenges of natural and anthropogenic induced climate change events. Total forest and other wooded land together comprise 44.74% (6.61 million ha) of the total area of the country (DFRS Nepal, 2015). The distribution of forest ecosystems can be observed distinctly according to altitudinal gradient from less than 1000 m to 4000 m. The broad forest types in Nepal are tropical (below 1000 m), subtropical broadleaved forests (1000–2000 m), subtropical pine forests (1000–2200 m), lower temperate mixed broadleaved forests (1700–2200 m), lower temperate broadleaved forests (1700–2700 m), temperate coniferous forests (2000–3000 m), upper temperate broadleaved forests (2200–3000 m), upper temperate mixed broadleaved forests (2500–3500 m), subalpine forests (3000–4100 m), alpine shrub (above 4100 m) (FRA 2000).

There are four climatological seasons namely pre-monsoon (March–May) that is hot and dry, the summer monsoon (June–September) is characterized by high humidity and precipitation, the post-monsoon (October–November) with reduced rainfall and winter (December–February) that is dry and cold (Kansakar et al., 2004). The temperatures in the Tarai and Mid-Hill region of Nepal are gradually increasing over the last few decades and expected to rise by 1.48⁰C, 2.88⁰C and 4.78⁰C respectively by 2030, 2060 and 2090 (Pradhan et al., 2013). The amount of precipitation and its distribution is determined by the annual monsoon system. The changes scenario of temperature and precipitation regimes helps to increase the number of wildfires in Nepal.

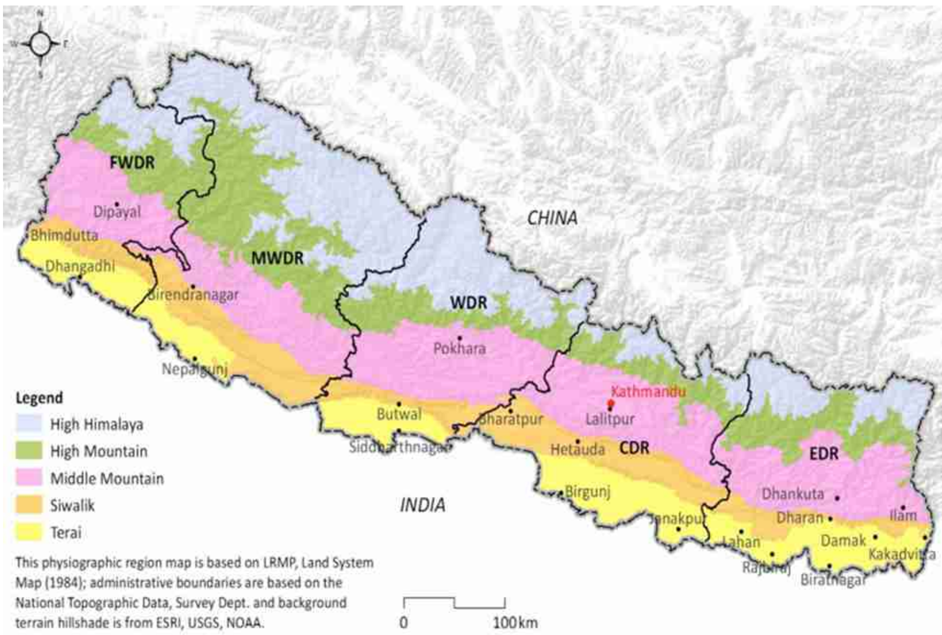

Figure 1 : Physiographic regions of Nepal (Adapted from DFRS, 2015)

Data sources and collection methods

The active fire data was acquired from the Moderate-Resolution Imaging Spectroradiometer (MODIS) device on NASA's Terra and Aqua satellites during the period 2000-2016 as data source for mapping and analyzing the wildfire incidences and forest burnt area. The resolution of MODIS image is 1 km x 1 km which records four times fire incidence observations per day basically on 1030 and 2200 hours from Terra and 0130 and 1330 hours from Aqua. During this period, wildfire incidences were driven from MODIS with confidence levels of 1-100%, but we use the high confidence data set (showing over 50% confidence level). The total numbers of wildfire incidence was divided into two categories like period from 2000 to 2015 and in 2016. The coordinates of wildfire points and the date of wildfire incidences were obtained from the MODIS active fire products (version 5.1:https://firms.modaps.eosdis. nasa. gov/download/).

The data related to burnt area were acquired from MODIS in the form of GEOTIFF images having the clear distinguishable pixels of burnt area (including burnt-date information). The monthly burnt area product (MCD45A1) having level 3 gridded (500 m resolution) was downloaded from the ftp server (ftp://ba1.geog. umd.edu/Collection5/TIFF/Win18/). In the next step, pixels showing the burnt area were extracted. The extracted image was processed geospatially in Arc Map 10.1. Then, the data showing the wildfire incidence and burnt area were categorized into two groups particularly data from 2000 to 2015 under first group and data of 2016 under second group. The accuracy of burnt area and number of wildfire incidence was checked/verified by comparing with the general accuracy statement of MOD14 product performance and direct field observation. Moreover, the desktop review of related literatures was carried out to explore the incidence and burnt area. The literature includes newspaper, article, report and electronic media.

Data analysis

The collected data of wildfire incidence and burnt area were analyzed using Microsoft Excel. The trends analysis and desktop review were used to find the trends of wildfire events and to compare the wildfire incidence, burnt area, burning days and density of wildfire from 2000 to 2015 and in 2016. The affected polygons showing the wildfire were counted and their areas were calculated. The clip function was applied to extract the wildfire affected area in ArcGIS. Moreover, the comparision maps of wildfire incidence were prepared by using the similar process of ArcGIS. In addition, the wildfire incidence and burnt area are presented in the climatological seasons namely pre-monsoon period (March-May), summer monsoon (June-August), post-monsoon (September-November) and winter (December-February).

Results and Discussion

Wildfire trends

Spatially and temporally, wildfire incidents and burnt areas were found to be varying. Over all recorded wildfire incidences were 35374 and the burnt area was 1723920 ha from 2000 to 2016 in Nepal. The higher wildfire incidences and burnt area detected in the years 2005, 2009, 2012, 2014 and 2016. Moreover, the wildfire incidences and burnt area were found to be increased over the 17 years period (Fig. 2), which may be due to the accumulation of huge fine fuel like dry and thick ground litter, grasses and coarse fuel particularly debris, stumps, dry branches, litters, bush and log are highly influencing materials to accelerate the wildfire. Huang et al. (2015) showed that about 27% wildfire incidence probably increase by 2050 relative to the 2000 levels in the world. Pechony and Shindell (2010) depicted that an unprecedentedly fire-prone environment in future may be the cause of climate change. Moreover, Girardin and Mudelsee (2008) showed that there may be increase in wildfire by about 34% by 2061 and 2100 in northwestern Ontario and eastern boreal Manitoba. Similar results

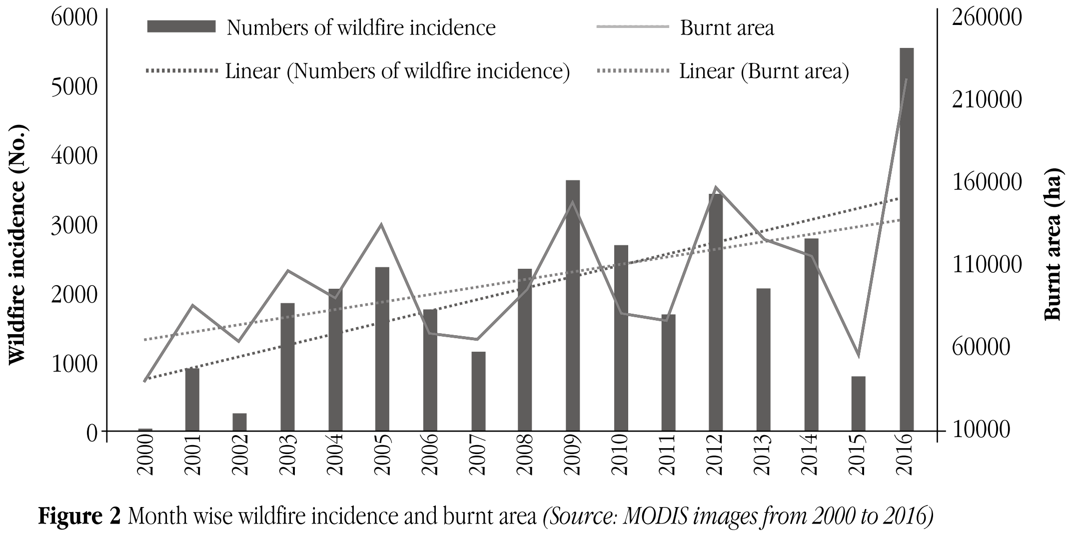

Figure 2 Month wise wildfire incidence and burnt area *(Source: MODIS images from 2000 to 2016)*

have been shown by Westerling et al. (2006), which depicted that the catastrophic wildfires have been increased in recent decades in both Southern United States and other parts of the world. These findings support the results of the present research work.

Month wise wildfire activities

The months of wildfire incidence were found to be increased in 2016 compared to the average annual wildfire incidence before 2016 (2000-2015). The higher wildfire incidence 5394 (72%) occurred in April 2016, whereas in the same month there was average 940 (52%) wildfire incidence from 2000 to 2015. It was followed by March, May and February (Fig. 3). This indicates that the April is the most wildfire vulnerable month in compared to other months.

Wildfire activities

The analysis showed that there was the variation in overall annual wildfire incidences and burnt areas. The higher incidences 5630 and burnt area 222046 ha was recorded in 2016 in compared to average annual incidence 1865 and burnt area 93867 ha from 2000-2015 (Fig. 4). Moreover, the status of wildfire incidence during 2000-2015 and 2016 was demonstrated in the maps, which compare status of wildfire incidence (Fig. 5).

The similar results showed in India, with 30% increase in wildfire incidence in April 21, 2016 compared to 2015 during fourth months of active fire reason (Mallapur, 2016). This result is in consistent to the present findings.

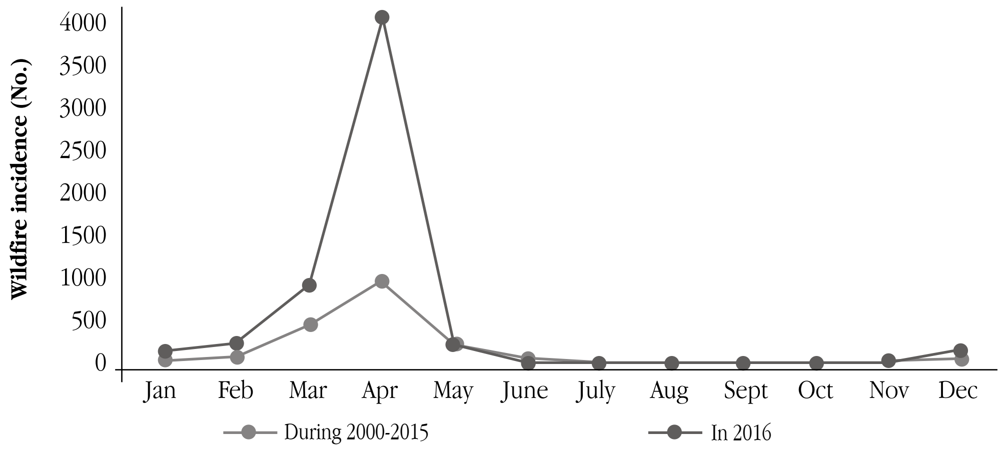

Figure 3 Month wise average annual wildfire incidence

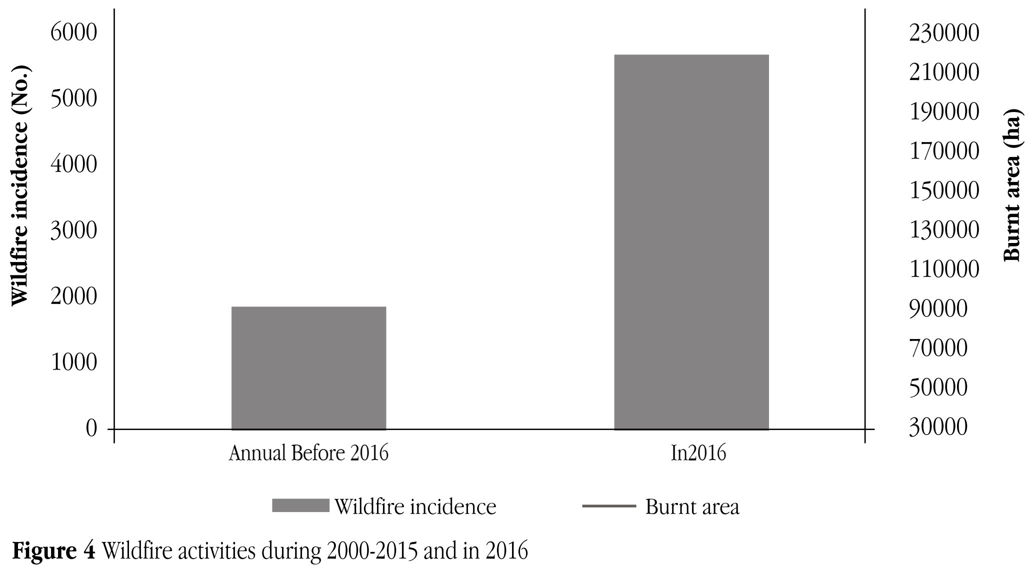

Figure 4 Wildfire activities during 2000-2015 and in 2016

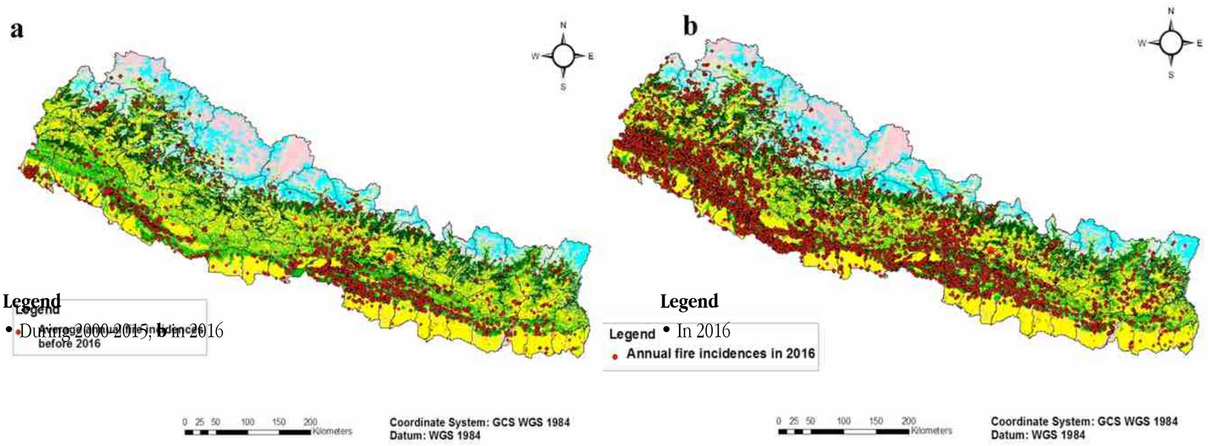

Figure 5 Wildfire incidence **a** during 2000-2015, **b** in 2016

Seasonal wildfire activities

The higher wildfire incidence record was found in pre-monsoon and winter seasons in 2016 compared to period from 2000 to 2015 (Fig. 5). Approximately 90% wildfire incidences were recorded in pre-monsoon season (March, April and May), while 87% were recorded during 2000-2015 in the same season. Similarly, winter was recorded as the second highest wildfire incidence season during 2000-2015 as well as in 2016. However, no wildfire incidence recorded during summer and post-monsoon seasons. Matin et al. (2017) showed the 89% wildfires occurrence during the pre-monsoon season (March-May) in Nepal. Similar study carried out by Shu et al. (2001) depicted that the most fire-hit time is February, March and April in South and Southwest forest areas in China. Moreover, observed higher wildfires were reported in central India during the March and April due to long dry seasons and droughts (Giriraj et al., 2010). These are supportive to the present research findings.

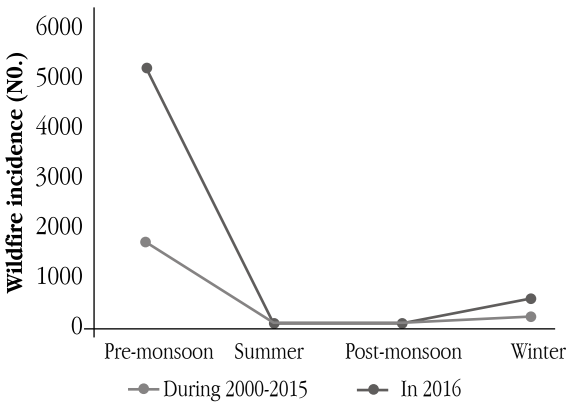

Figure 6 Seasonal average wildfire incidences

Length of wildfire days

The annual record of wildfire days found more in 2016 in comparison to period from 2000 to 2015. Specifically, there were more wildfire days (140) in 2016. However, it was less (138) days during 2000-2015. On an average, 40 wildfire incidences with 1586 ha forest burnt area per day recorded in 2016 and only 14 incidences with 640 ha forest burnt area per day was found during 2000-2015 showing 35% wildfire incidence with 40% burnt area higher in 2016 compared to period from 2000 to 2015.

Moreover, the higher numbers of wildfire days (25) recorded in April. Around 166 incidences with 7528 ha burnt area per day were recorded in 2016. There were about 38 incidences with 1894 ha burnt area per day in the same month during 2000-2015 (Table 1). Similarly, the March, May and December were recorded as the second, third and fourth month of higher wildfire days, respectively. The July and August were recorded with nageglible wildfire days and months like January, February, September, October and November were recorded as months with no wildfire days. Bowman et al. (2017) showed an increase in days conducive to extreme wildfire events by 20% to 50% in the disaster-prone landscapes, particularly in sub-tropical Southern Hemisphere and European Mediterranean Basin. This finding is also consistent with the present study. Moreover, Yue et al. (2013) depicted that wildfire is nearly 65% in the Pacific Northwest, Eastern Rocky Mountains/Great Plains regions. Richtel and Santos (2016) showed wildfire season has increased significantly longer in the past 30 years in New Mexico. All these results are in agreement with the present research findings.

Table 1: Length of average annual wildfire days

Month	Average annual wildfire days during 2000-2015 Wildfire Days	Wildfire incidence	Burnt area ha	incidence /day	burnt area ha/day	Annual wildfire days in 2016 Wildfire Days	Wildfire Days	Burnt area ha	incidence /day	burnt area ha/day
Jan	9	22	1107	3	123	24	142	5666	6	236
Feb	16	80	4026	5	252	24	221	10051	9	402
Mar	24	442	22246	18	927	19	885	18798	47	989
Apr	25	940	47362	38	1894	25	3991	180672	166	7528
May	19	239	12029	13	633	14	199	5329	14	381
June	7	42	2114	6	302	2	6	0	3	0
July	0	0	0	1	0	0	0	0	0	0
Aug	0	0	0	1	0	0	2	0	0	0
Sept	2	3	151	2	75	2	2	22	1	11
Oct	4	6	302	2	75	5	12	0	2	0
Nov	14	34	1711	2	122	14	24	202	2	14
Dec	18	54	2818	3	157	11	146	1304	4	9
Total	**138**	**1865**	**93867**	**93**	**4561**	**140**	**5630**	**222046**	**254**	**9571**
Average wildfire	-	-	-	14	680	-	-	-	40	1586

Table 2 : Wildfire densities

Physiographica region	Wildfire densities during 2000-2015 Forest Area in km^2	Total wildfire	Wildfire incidence /km^2	Total Burnt area ha	Burnt area/km^2	Wildfire densities in 2016 Total wildfire	Wildfire incidence/km^2	Total burn area (ha)	Burnt area/ km^2
High Mountain/ high Himalaya	24763	221	0.01	45474	1.8	656	0.03	25873	1.0
Middle hill	23161	678	0.03	7630	0.3	2057	0.09	81128	3.5
Siwalik	13964	748	0.05	30985	2.2	2236	0.16	88187	6.3
Tarai	4211	218	0.05	9778	2.3	681	0.16	26858	6.4
Total	**66099**	**1865**	**0.14**	**93867**	**6.7**	**5630**	**0.43**	**222046**	**17.2**
Average	-	-	0.03	-	1.4	-	0.09	-	3.4

Density of wildfire incidence and burnt area

In Nepal, average density of wildfire incidence varied according to physiographical regions. It was higher (0.09) incidence with 3.4 ha forest burnt area per km^2 in 2016 than the average annual wildfire incidence of 0.03 with 1.4 ha burnt area per km^2 during 2000-2015 (Table 2). Specifically, wildfire density was found to be higher in Tarai region. The recorded wildfire incidence and burnt area in this region was respectively 0.16 and 6.4 ha per km^2 in 2016. However, the annual average annual incidence was 0.05 with burnt area 2.3 ha per km^2 during 2000-2015.

Similarly, second higher wildfire density was found in Siwalik with having recorded 0.16 wildfire incidence with 6.3 ha forest burnt area per km^2 in 2016, whereas 0.05 wildfire incidence with 2.2 ha forest burnt area per km^2 during 2000-2015. On the other hand, the lowest density of wildfire incidences and burnt area were found in the High-Mountain and Himalayan region, where 0.03 incidence with 1.0 ha forest burnt area was recorded from 2000 to 2015. In India, Banerjee (2016) showed higher wildfire densities in April. Moreover, California Department of Forestry and Fire Protection (CAL FIRE, 2016) reported higher wildfire densities across the California in 2016. Both research results are in agreement with the present research findings.

Conclusion

The spatial and temporal wildfire incidence and burnt area varied and it was found to be in increasing trends over the 17 years (2000-2016) period. The wildfire incidences, burnt area, wildfire density and length of the burning days were found to be higher in 2016 in comparison to 2000-2015. Moreover, the April was found to be the most wildfire vulnerable month. However, January, February, September, October and November were found to be the months of very less wildfire incidences, and July and August were observed to be the months of negligible wildfire incidence. Seasonally, the pre-monsoon was found to be highly wildfire sensitive period. Overall, there was higher wildfire incidence and burnt area per km^2 in 2016 than average annual wildfire incidence and burnt area per km^2 during 2000-2015. These findings will be useful for wildfire ecology, wildfire manager and wildfire management policy makers.

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Research Article

WILDFIRE DYNAMICS AND ITS EFFECTS ON THE FOREST RESOURCES AND PUBLIC PROPERTY IN NEPAL

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ABSTRACT

NASA (National Aeronautics and Space Administration) has detected several intensive wildfires from the local to global level in 2016. However, deeper study on the dynamics of wildfire and its consequences are still inadequate. This study was carried out to find wildfire dynamics and its effects on the forest resources and public property in Nepal. Moderate Resolution Imaging Spector-Radiometer (MODIS) was used for active fire data of 2016 in Nepal. Wildfire-related national and international published articles, report, website and media were reviewed. Data were analyzed using ArcGIS and MS Excel. The result showed an abnormal wildfire incidence areas in 2016, adverse effect on the forest resources and public property. One hundred forty burnt days were recorded. Density of wildfire incidence and burnt area were found to be 0.09 number and 3.4 hectares per km^2, respectively, which was around 33 % more than of the last 15 years. The huge forest resources and its tangible as well as intangible services were lost during the year of 2016. Loss of forest resources account for about NRs 11,750,000 (US$ 107,798) as per local market price for the year. Total eleven people were killed and over hundred people injured. The findings of the present study will be useful baseline information for implementers, researchers and decision-makers in future.

Keywords: Burnt area, Density, Wildfire incidence, Wildfires day

INTRODUCTION

Wildfire is a critical disturbance factor in the forest ecosystems, which acts as a double-edged sword in the natural circumstance. It is considered an important part of ecosystem services, providing nutrients and recycling material and is also one of the important disturbance factors in boreal forests (Shorohova *et al.* 2011, de Groot *et al*. 2013). Wildfires also play an important role in several atmospheric chemistry and climate feedback mechanisms (Fiore *et al*. 2012). The impacts of wildfires on human society are largely determined by population growth and spatial distribution (Knorr *et al*. 2016). According to Global Forest Resources Assessment (FAO 2010), around 19.8 million hectares of forests are affected by fire annually in 118 countries of the world. Moreover, 3.73 million hectares of forests are affected annually in India (Satendra & Kaushik 2014). Wildfire occurrence and severity have been increasing in recent decades and will continue to increase due to climate change (Doerr & Santin 2016) and it showed that approximately 0.4 % of the total land surface was recorded as the burnt area per year in the world (Randerson *et al*. 2012). Giglio *et al*. (2013) depicted that global area was nearly 350 MHa annually.

Tropical Asia has experienced the highest biomass burning region in Asia due to the extreme climatic conditions (Streets *et al*. 2003). Wildfire behavior is influenced by the distribution of forest resources (fuels), topography and favorable environmental conditions (Parisien & Moritz 2009). According to India State of Forest Report (MEF/India 2011), more than 95 percent of the forest fires in the Indian were anthropogenic causing wide range of adverse ecological, economic and social impacts. NASA (Lynn 2017) data has recorded warmer year in 2016 than the mid-20th century. It has been reported to be responsible for the increase of 1.78 °F (0.99 °C) in average global temperatures.

Global temperature has been increased by approximately 0.2 °C per decade over the last three decades (Hansen *et al*. 2010). The study done by Kothawale *et al*. (2010) highlighted that the mean temperature during the pre-monsoon season (March-May) was increasing by 0.42 °C per 100 years. Hartmann *et al*. (2013) noted that the warming trend was increased globally, which could be associated with variations in the climate system. Annual temperature was increased in India as well (Rohini *et al*. 2016). The extreme severe heat waves (> 40 °C) events were recorded on 11 April and 21 May, 2016 which were rare events (Singh *et al*. 2017). The changing scenario of temperature and precipitation is resulting in the increase in the number of wildfires (Negi *et al*. 2012).

In general, months between March-May were noticed as the driest season in Nepal (GoN/MoE 2010). The record of fire incidence has been increasing annually in Nepal. Parajuli *et al*. (2015) showed that wildfire result in loss of natural vegetation as well as the destruction of human settlements. MODIS sensors recorded 29844 wildfire incidences in Nepal from 2003 to 2013. Based on > 50 %

confidence level, 12269 fire incidences occurred within forest, grasslands, shrub lands, and outside protected areas of Nepal (Matin *et al*. 2017). Moreover, Jenner (2017) mentioned that there was higher smoke and wildfire in a satellite image of Nepal for year 2016 and hence it results in adverse effects on the forest resources and public property. In this context, several questions were raised regarding the noticeable wildfire events in the year of 2016 for the research. For example; what could be the pattern of wildfire incidence and burnt area in 2016, what will be its consequences in forests and public property? This research was carried out to address these questions showing the wildfire incidence, burnt area, burning days, density of wildfire and its effects on the forest and public property for 2016 in Nepal.

MATERIAL AND METHODS

Study area

The study area covers the entire Nepal, which situated between latitude 26^0 22' N and 30^0 27' N and longitude 80^0 40' E and 88^0 12' E with area of 147 181 km^2. It is divided into five physiographic zones namely High Himalayan, High Mountains, Middle Mountains, Siwalik and Terai (Fig. 1). Country exhibits mostly mountainous terrain with an elevation ranging from 58 m to 8848 m above mean sea level (amsl) at Mount Everest. Nepal is considered biodiversity hotspots, as it is home for 35 forest types, 75 vegetation types and 118 ecosystems (Chettri *et al*. 2008). However, these ecosystems are facing challenges due to natural and anthropogenic induced climate change and wildfire. Total forest including other wooded lands comprised 44.74% (6.61 million ha) in the country (DFRS 2015).

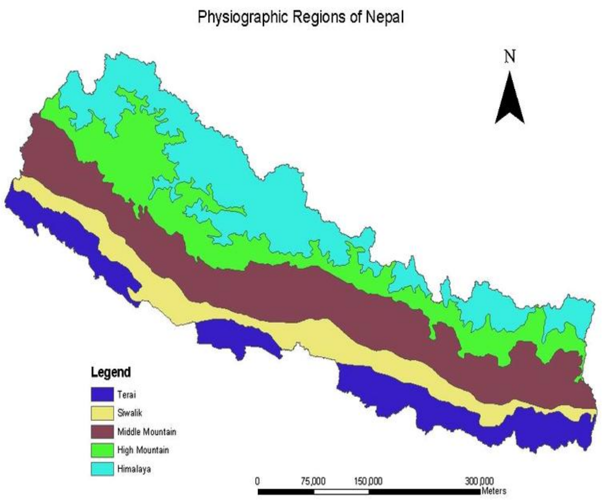

Fig. 1. Physiographic regions of Nepal

Dobremez (1972) have identified 118 ecosystems and classified Nepal into 4 domains and 11 sub-levels and provided six vegetation categories based on an altitudinal classification (bio-climatic zones) as; tropical (below 1,000 m altitude), sub-tropical (1,000 to 2,000 m altitude), temperate (2,000 to 3,000 m altitude), sub-alpine (3,000 to 4,000 m altitude), alpine (4,000 to 5,000 m altitude) and nival (above 5,000 m altitude).

Four climatological seasons has been divided as; hot and dry pre-monsoon period (March-May), the summer monsoon (June–September) which is characterized by high humidity and precipitation, the post-monsoon (October–November) with reduced rainfall, and dry and cold winter period (December–February) (Kansakar *et al*. 2004). Terai and middle mountain regions of Nepal are gradually experienced of the increasing temperatures due to climate change. Specifically, it was reported that about 3 °C is increased during the summer months over the last few decades that are expected to rise by 1.48 °C, 2.88 °C and 4.78 °C by 2030, 2060 and 2090, respectively (Pradhan *et al*. 2013). A significant positive trend in annual and seasonal maximum temperature was reported (DHM, 2017). This changing scenario of temperature and precipitation might be responsible for increasing in the number of forest fires in future, indicating Nepal to be vulnerable to wildfire.

Data sources and collection methods

The active fire data from the Moderate-resolution Imaging Spectro-radiometer (MODIS) device on NASA's Terra and Aqua satellites date of 2016 was used as the main data source. The resolution of MODIS image is 1 km × 1 km which records four times fire incidence observations per day basically in 1030 and 2200 hours from Terra and 0130 and 1330 hours from Aqua. During this period, a wildfire incidence in 2016 was driven from MODIS products with confidence levels of 1–100 %. It filtered out the records less than 50 % confidence level and counted only over 50 % confidence level. The coordinates of wildfire points and the date of wildfire incidence were obtained free of cost from the MODIS active fire products (version 5.1). These point data were achieved from https://firms.modaps.eosdis.nasa.gov/download/ in the form of shape-files which were further analyzed in Arc Map 10.1.

MODIS also provide the data of a burnt area in Geo-TIFF format images with clearly distinguished burnt area pixels (including burnt-date information) from other adjacent pixels. The monthly level 3 gridded (500 × 500 m^2) burnt area product (MCD45A1) was downloaded from the ftp server (ftp://ba1.geog.umd.edu/Collection5/TIFF/Win18/). Burnt area pixels within the study area were extracted from TIFF images and processed in Arc Map 10.1 to calculate the burnt area. The accuracy of the burnt area and number of wildfire incidence was checked by comparing with the general accuracy statement of MOD14 product performance and direct field observation. Moreover, the desktop review of the related literature was carried out to find out the wildfire incidence and burnt area. Besides, the published and unpublished newspaper, article, reports were reviewed.

Data analysis

The collected data of wildfire incidence and burnt areas of 2016 was analyzed using Microsoft Excel. The linear regression model was used to find the dynamics of wildfire events and its effects on forest resources and public property sector. Wildfire point was estimated to count the polygon. Burnt area pixels within the study area were then extracted from the TIFF images using clip function processed in Arc Map 10.1. Again clip function was applied to extract Nepal shape-file and then calculated the burnt area.

RESULTS

Wildfire incidence and burnt area

The wildfire incidence (Fig. 2) and burnt area (Fig. 3) were recorded higher across the country, basically concentrated in the Province No. 5 and 7 of Nepal. The low land of the forests has noticed higher numbers of fire ignitions, indicating high wildfire prone areas of Nepal. Furthermore, the result showed that there were 5630 wildfire incidences and 222046 ha burnt forest area in 2016. The month of April was noticed with highest wildfire incidence and burnt area, with 72 % and 81 % coverage, respectively and it was followed by March, May, February and January as shown in Fig. 4.

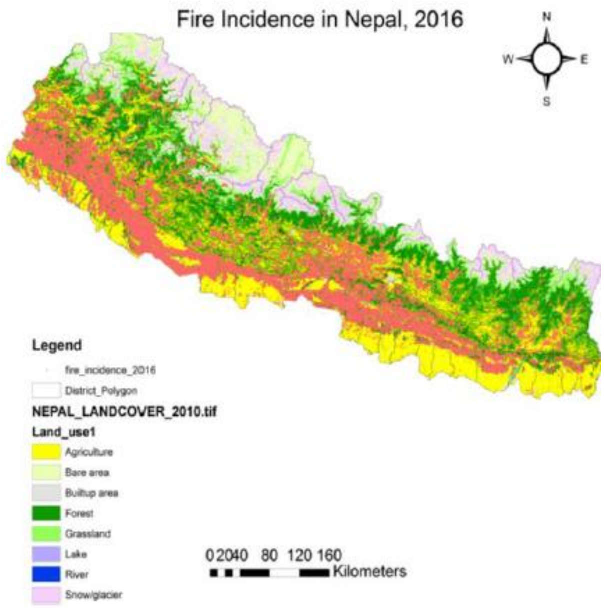

Fig. 2. Wildfire incidence in Nepal in the year of 2016

Seasonal patterns of wildfire incidence and burnt area

The wildfire incidence and burnt area varied according to climatological seasons. The result showed that pre-monsoon had higher wildfire incidence and burnt area than other seasons. It covered approximately 90 % wildfire incidence and 92 % burnt area out of the total events (Fig. 5). It is due to thick, hot and dry fuel. It was followed by winter season (7 %). The summer monsoon and post monsoon had lower wildfire events.

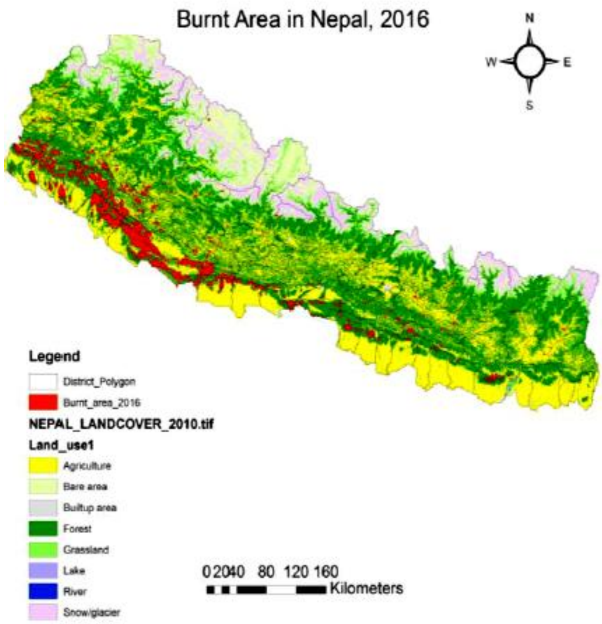

Fig. 3. Wildfire burnt area in the year of 2016

Wildfire incidence days

Total 140 days were recorded as wildfire incidence in 2016. The wildfire days noticed minimum 0 and maximum 25 in each month. Out of the total wildfire days, 41 % wildfire days were recorded in active fire season of March, April and May months. An average of 40 numbers of wildfire incidence and 1586 hectares burnt area recorded per day. An average of 12 wildfire day, 469 numbers of wildfire incidence and 18504 ha burnt area were recorded in a month in 2016 (Table 1). The maximum wildfire incidence (3991 number of incidence) and burnt area (7528 ha) was noticed in April.

Densities of wildfire incidence and burnt area

The study showed the densities of wildfire incidence and burnt area, which cover 0.09 number of wildfire incidence and 3.4 hectares forest area burnt per km^2 (Table 2). The highest densities of wildfire incidence and burnt area showed in Terai (0.22 number of incidence and 6.4 ha burnt area per km^2) and comparatively lower incidences in high mountain and high Himalayan regions (0.03 number of incidence and 1.0 ha burnt area per km^2). The second and third wildfire incidence and burnt area densities occurred in the Siwalik and middle mountain regions, which cover 0.16 number of wildfire incidence with 6.3 ha burnt area and 0.09 number of wildfire incidence with 3.5 ha burnt area, respectively.

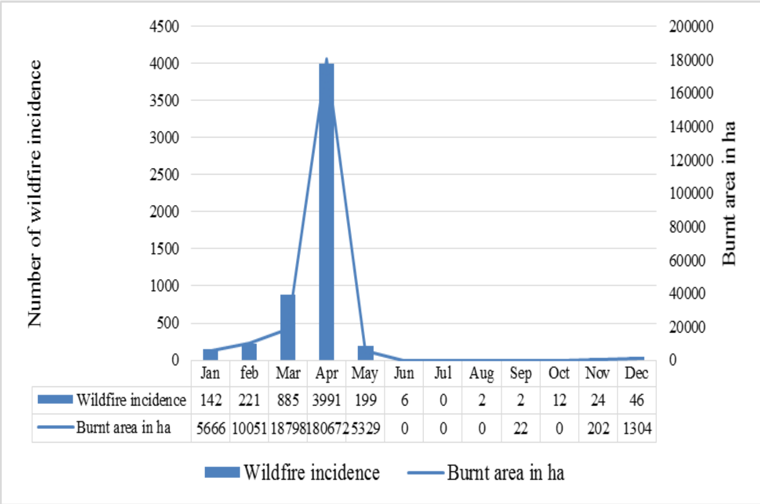

Fig. 4. Monthly based wildfire incidence and burnt area

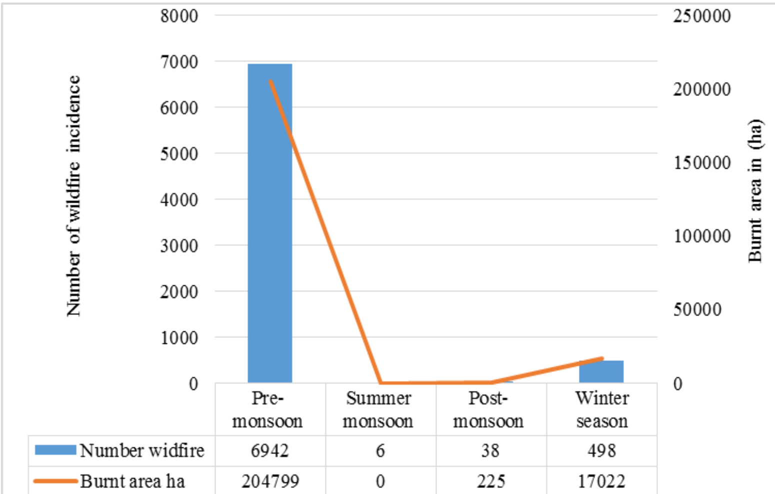

Fig. 5. Seasonal based wildfire incidence and burnt area

Table 1. Wildfire days and densities

Month	Wildfire Days	Wildfire Incidence	Burnt Area (ha)	Average incidence (number/day)	Average Burnt (area/day)
Jan	24	142	5666	6	236
Feb	25	221	10051	9	402
Mar	19	885	18798	47	989
Apr	24	3991	180672	166	7528
May	14	199	5329	14	381
June	2	6	0	3	0
July	0	0	0	0	0
Aug	0	2	0	0	0
Sept	2	2	22	1	11
Oct	5	12	0	2	0
Nov	14	24	202	2	14
Dec	11	146	1304	4	119
Total	140	5630	222046	-	-
Average	12/month	469/month	18504/month	40/day	1586/day

Table 2. Wildfire densities in 2016

Physiographical Region	Forest Area (km^2)	Total Wildfire Incidence	Wildfire Incidence (km^2)	Burnt Area (ha)	Burnt Area (ha/km^2)
High Mountain & Himalayan	24763.4	656	0.03	25873	1.0
Middle Mountain	23160.94	2057	0.09	81128	3.5
Siwalik	13964.15	2236	0.16	88187	6.3
Terai	4210.82	681	0.16	26858	6.4
Total	66099.31	5630	0.43	222046	17.2
Average			0.09		3.4

Wildfire incidences in different land cover types

Total 66 % of the wildfire incidence occurred in the forest area, indicating the higher wildfire incidence than other land covers. It was followed by grass (17 %), shrub-land (10 %) and other lands (6 %) respectively (Fig. 6). The other land, considered as a nearest abandoned land of agriculture were covered by bushes. It showed that forest was highly wildfire risk zone than other land covers in Nepal.

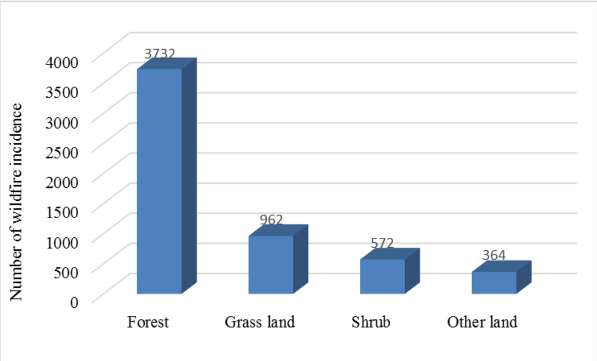

Fig. 6: Wildfire intensity in land cover

Damage and loss

The research showed the approximately 0.22 million hectares of forest was burned, which cover 3.4 % of the whole forest area of Nepal. The huge forest biomass, forest ecosystem service, and public property were destroyed by wildfire across the country. Total of 2500 cubic feet of highly valuable timber and 12500 cubic feet fuel-wood were lost and damaged. Based on the local market price, the loss of timber and fuel-wood was equivalent to NRs 11,750,000 (US$ 107,798). The timber price in the local market was NPR 4500 per cubic feet and fuel-wood NPR 40 per cubic feet. During the time of calculation, the foreign currency exchange rate was 1 USD = 109 NPR. Besides, the leaf litter, herbs, and shrub were almost completely lost and damaged. The poles and timbers were the least damaged due to surface fire. In addition, there was a noticeable loss of biodiversity, loss of wildlife habitat, loss of fodder and other natural resources with natural regeneration.

Eleven people were killed by wildfire across the country in 2016. They were living closest to the forest and involved in the wildfire control process during the forest fire. Over 100 local people were injured during the wildfire control. A large number of temporary house and domestic animals were damaged during the fire season. There was lack of skill, knowledge, and equipment for preventive and control measures of the wildfire at local level. In addition, large number of wildlife and their habitat were lost and damaged. The forests of Terai, Siwalik and Middle Mountain regions were highly affected by the wildfire. The forest of Surkhet, Bardiya, Dang, Kailali, Kanchanpur, Argakhanchi, Rupandehi Kapilbastu, Nawalparasi, Bara, Parsa, Rautahat, Mahottari, Dhanusa and Sindhuli districts was noticed as the highly affected by wildfire (Matin *et al.* 2017).

DISCUSSION

The study focused on the analysis of the wildfire scenario of 2016 and its effects on the forest resources and public property of Nepal. The wildfire in Nepal was recorded abnormally high and its' consequence was found to adversely affect the forest resources and public property. Forests are most susceptible to fire due to the dominance of the fire-prone tropical broad-leaved related vegetation and heavy fuel loads, rising temperatures, and low rainfall. The forest fuel was accumulated in large quantity in the forest because of fewer numbers of forest fire events in the previous year in 2015 (Westerling 2016). Approximately, 72 % wildfire incidence and 81 % burnt area was recorded in the month of April. Moreover, high wildfire events were also detected in March, May and February months and nominal incidence of wildfire noticed in other months. Petoukhov *et al.* (2018) study showed high-temperature conditions at the surface in that area, causing an increased wildfire hazard in Canada during 2016. According to Upadhyay (2016), wildfire was reported in numerous places across the Indian state of Uttarakhand in 2016. The wildfire incidences were recorded 20,667 during the four months of 2016 basically in the Himalayan foothills and in central and eastern India (Trivedi & Anupam 2016). During 2016, local, state, federal, and tribal firefighting agencies responded to 6,954 wildfires that burned 669,534 acres across the entire state of California (Pimlott 2016).

The study showed that a higher wildfire incidence and burnt area occurred in April and none in July and August. It was followed by March, May, and February as second, third and fourth higher wildfire incidence respectively. In an average, 92 % wildfire incidence and burnt area recorded in the pre-monsoon season due to warmer climate and abundant dry fuel. This result was consistent with the research findings of (Matin *et al*. 2017), which showed the 89 % wildfire occurring during the pre-monsoon season (March-May) in Nepal. A similar study was done by (Shu *&* Kou 2001) which depicted that the highest fire-hit time was in February, March, and April in South and Southwest forest areas in China. Moreover, in central India, higher wildfire was observed during the March and April due to prolonged dry seasons and droughts (Giriraj *et al*. 2010), which was similar to the result of our research. In 2016, Portugal suffered many fires that burnt over 100,000 hectares of land and contributed significantly to the overall results of the fire season (Knorr *et al*. 2016). Schaphoff *et al.* (2016) reported that the current fire-affected area is 20 % and forest lost to stand-replacing fires has also increased in forests in Russia.

Our result recorded 140 wildfire days in 2016. Westerling (2016) study showed 138 days of wildfire in last decade. According to MEFC/India (2017), around 33664 forest fires were detected in India in 2016, which covered 52.4 fire per 1000 square kilometer. Approximately, 55% of wildfires had risen in December 2016 in India (Jenner 2017). The analysis showed that 11 people were killed and over 100 local people were injured due to the wildfire in Nepal. In 2016, a forest fire was noted in numerous places across the Indian state of Uttarakhand. Seven cases of human fatalities and loss of around Rs 550 crore recorded owing to damages caused by forest fires (MEFC/India 2017). A total of 3,390 civilian deaths and 14,660 fire injuries occurred, which was an increase by 3.4 % compared to the year 2015 and the damaged of $10.4 billion worth property was recorded in the United States during 2016 (Hylton 2017).

CONCLUSION

The wildfire incidence and burnt area were recorded abnormally in 2016 that adversely affected the forest resources and public property of Nepal. The April month and pre-monsoon season showed highest numbers of wildfire incidence and burnt area. Approximately, 3 °C temperature increased during the summer months over the last few decades. Wildfire days was found to be 2 days longer with a high density of fire incidence and burnt area per km^2 in comparison to previous years. Terai region was noticed to record highest wildfire and lowest in High Mountain and High Himalayan. The huge forest resources and its services were lost during this year. In addition, 11 people were killed and over 100 local people were injured in the same year. The findings can be useful to local forest managers, researcher and policymakers as baseline information.

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Wildfire Dynamics and Occasional Precipitation during Active Fire Season in Tropical Lowland of Nepal

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ABSTRACT

Occasional precipitation plays a vital role in reducing the effect of wildfire. This precipitation is especially important for countries like Nepal, where wildfires are a common seasonal event. Approximately 0.1 million hectare of forest area is affected annually due to wildfires in active fire season. The study on the relation of these forms of occasional precipitation with wildfire incidence is still lacking. This research was objectively carried out to examine the correlation of occasional precipitation with wildfire incidence and burnt area. The Moderate Resolution Imaging Spector-Radiometer (MODIS) satellite images and precipitation records for 15 years gathered from Department of Hydrology and Metrology were used as input data for this study. The images were analyzed by using ArcGIS function while the precipitation records were analyzed by using Statistical Package for the Social Science (SPSS) program. The linear regression model was applied to find correlation of occasional precipitation with wildfire incidence and burnt area. Analysis revealed decreasing trend of precipitation in study area. We found significant correlation ($p<0.05$) of precipitation with wildfire incidence and burnt area. Findings will be useful for policy makers, implementers and researchers to manage wildfire in sustainable basis.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change showed that global warming has been a challenge for living beings in the world. Biodiversity loss, desertification and food insecurity are major negative impacts of climate change (IPCC, 2015). However, there are more impacts like increasing incidence of fires inside and outside forests at the micro level. The increasing days of warming cause fewer rainy days in monsoon and other seasons. Warming helps to dry the fuel in the forest which leads to fire incidence. Occasional precipitation, which can be defined as precipitation occurring at irregular or infrequent intervals in active fire season, assists to reduce the fire incidence and its effects.

Wildfire frequency, seasonality, intensity and extent are variables that are more likely to control forest distribution (Foster et al., 1998). Fire behaviors are affected by various factors, such as weather conditions, human activities, fuel characteristics, and land use dynamics. Wildfires are considered as one of the major forces shaping Mediterranean landscape and controlling vegetation communities' succession and structure (Millington et al., 2009). Wildfires also contribute to the development of the pattern of vegetation succession, the rate of which largely depends on the prevailing plant traits (Mouillot et al., 2003). Among these factors, climate change is considered to be a key factor attributing to wildfires regime. Climate is of fundamental importance in defining the conditions that permit fire. Thus, climate helps to shape geographic patterns of fire (Krawchuk et al., 2009).

Temporal variation in precipitation at seasonal, inter-annual, and inter-decadal timescales is widely recognized as a major driver of variation in wildfire frequency and extent in fire-prone regions (Swetnam and Betancourt, 1990). Fire frequency is expected to increase with human-induced climate change, especially where precipitation remains the same or is reduced (Stocks et al., 1998). A general but moderate increase in precipitation, together with increased productivity favors generation of more flammable fine fuels. The investigation of the role of either fuel or climate on the occurrence of large wildfires has been mainly based on the assumption that these are either limited by (a) climate or (b) fuel accumulation (Meyn et al., 2007). Models relating fire activity to weather parameters contribute to improve the understanding of the underlying mechanisms behind fire regimes and provide valuable information for fire management.

Nepal has been experiencing irregular wildfire events in recent years including trans-boundary wildfire and haze pollution (Government of Nepal, 2010). Around 0.1 million ha of forests are annually affected due to wildfire. The active fire season in the country ranges from March to May. There is no systematic and complete record of wildfire occurrence and their effects in Nepal (Bajracharya, 2001). Extreme climatic conditions have led to increased incidence of wildfire in recent years (MoE/GoN Nepal, 2010). The wildfire problems are acute for three to four months during the dry period between March and June every year (Bajracharya, 2002). Repeated incidence of fire has resulted in changes in many Terai forest ecosystems (Kunwar and Khaling, 2006). Community based fire management could be the key to overcome the recurring problems of forest fires in Nepal (Sharma, 2006). The precipitation pattern of Nepal is dominated by the presence of the monsoon circulation and its interaction with the topography, and the Siwalik and the Terai belt which generally receive less total seasonal rainfall compared to the middle hills (Kansakar et al., 2004). Of the total 75, 30 districts that are mostly allocated in the Siwalik and Terai region fall in high forest fire risk classes (Matin et al., 2017).

Developing countries like Nepal are still lacking research on the relation of the occasional precipitation with wildfire incidence including others parameters. Moreover, there is poor database management and lack of a clear understanding about the relation of climatic variables especially with the occasional precipitation and its severity of forest resources in the lowland of country. The context is complex and, therefore, several questions are raised. Specifically, what are the characteristics of occasional precipitation, and is there a relationship between precipitations and wildfire incidence including burnt area? This research was carried out to examine the relationship between the occasional precipitation and wildfire incidence, and burnt area in active fire season in one of the wildfire-prone districts, during the years 2000 through 2014.

2. METHODOLOGY

2.1 Study area

The study was conducted in Nawalparasi district located in the western lowlands of Nepal within latitude 27°21' to 27°47' and longitude 83°36' to 84°25' (Figure 1). The altitude ranges from 91 to 1936 m above average mean sea level. Terai and foothills of Siwalik are considered as low land (DFRS Nepal, 2015). It covers an area of 2,162 km^2, which is 1.5% of the total area of Nepal. About 55% (122,365 ha.) of the district is under forest cover. This study area was divided into three physiographic regions namely Terai, Siwalik and Hill which cover 22.5%, 61.6% and 16% of the district areas respectively. The Siwalik is a narrow strip of fragile hills extending east-west in between the Terai and Hill. The Terai is a fertile, flat land to the south of Siwalik. The Terai and Siwalik regions have a gentle slope up to 15°, while Hill range bears steep slope 15° -50°. There are four types of forest, namely lower tropical Sal (*Shorea robusta*) forest, Sal hill forest, and two Riverine forests (*Dalbergia sissoo* and *Acacia catechu*). Most of the forests are located in the Siwalik and Hill regions. The area is vulnerable to wildfire particularly during the summer season (March to April) when conditions are very dry, thereby causing loss of forest products and environmental degradation of forest.

2.2 Data sources and collection methods

Active fire data from the Moderate Resolution Imaging Spectroradiometer (MODIS) device on NASA's Terra and Aqua satellites dating from 2000 to 2014 was used as the main data source for mapping and analyzing the wildfire incidences. The resolution of MODIS image is 1 km × 1 km which records four fire incidence observations per day, basically on 1030 and 2200 h from Terra and 0130 and 1330 h from Aqua. The coordinates of wildfire points and the date of wildfire incidence can be obtained free of cost from the MODIS active fire products (version 5.1). Those obtained point data from https://firms.modaps eosdis.nasa.gov/download/, in the form of shape files, were further analyzed in Arc Map 10.1.

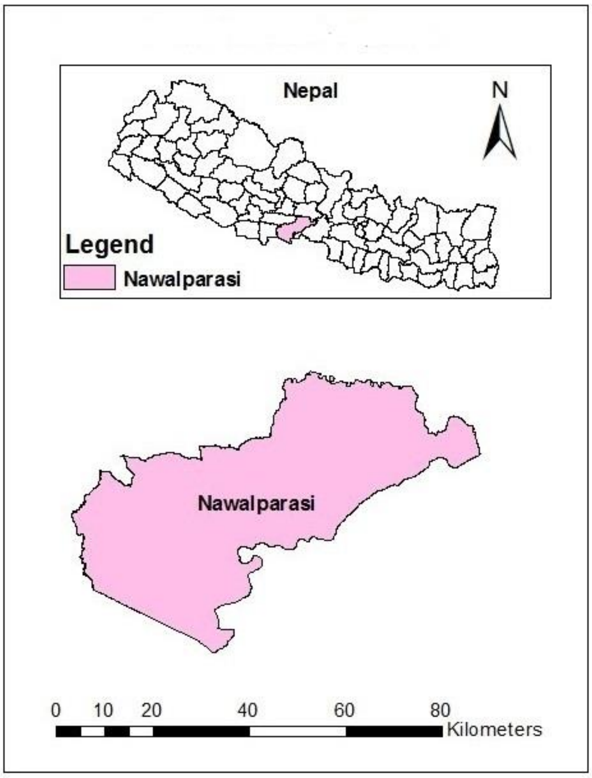

Figure 1. Location of study area

MODIS also provides the data related to burnt area in the form of GEOTIFF images with clearly distinguished burnt area pixels (including burnt-date information) from other adjacent pixels. The monthly level 3 gridded (500 m) burnt area product (MCD45A1) was downloaded from the ftp server (ftp://ba1.geog.umd.edu/Collection5/TIFF/Win18/). Burnt area pixels within the study area were then extracted from the TIFF images, processed in Arc Map 10.1 and the monthly burnt area data throughout the study period was calculated and analyzed. The accuracy of burnt area and number of wildfire incidence was checked by comparing with the general accuracy statement of MOD14 product performance and direct filed observation.

2.3 Data analysis

The collected data of wildfire incidence, burnt area and climatic variable over 15 years (2000-2014) was analyzed using Microsoft Excel and SPSS 20. The trend analysis and linear regression model were used to find the dynamics of occasional precipitation and its relation with wildfire incidence and burnt area. The wildfire point locations were further analyzed in Arc Map 10.1. Point count by polygon method was used to identify the number of wildfire incidence in the study area. Burnt area pixels within study area were then extracted from the TIFF images using clip function processed in Arc Map 10.1. Again clip function was applied to extract district boundary shape file of study area and then calculated the burnt area.

The daily data of the average annual occasional precipitation was compiled for three months of active fire season over the study period. The temporal data of average occasional precipitation was graphically plotted by using Microsoft Excel. The dynamics of occasional precipitation was demonstrated by trend lines especially in the month-wise and total average occasional precipitation of three months of active fire season. The records of numbers of wildfire incidence and burnt area of active fire season were presented in the bar graphs and lines for showing the historical patterns of wildfire incidence.

The relationship between wildfire incidence and burnt area against climatic variables, especially occasional precipitation, of active fire season was analyzed. The linear regression was used to find the relationship between precipitation and wildfire incidence including burnt area. The mean, standard error, standard deviation, maximum and minimum range of precipitation, number of wildfire incidence and burnt area were analyzed by descriptive statistical tool. The value of Pearson correlation (r) and r^2 were calculated and t-test was done at 5% level of significance to find out the correlation between occasional precipitation against the number of wildfire incidence and burnt area.

The validation was done to compare the research findings with other similar research works (Nickeson, 2016; Morisette et al., 2005; Csiszar et al., 2006). Moreover direct field observation and consultation with related key persons were carried out for validation purpose.

3. RESULTS AND DISCUSSION

3.1 Trends of precipitation in active fire season

The highest monthly total precipitation (562 mm) during the active fire season was found to occur in May and lowest (0 mm) in March and April over the 15 year period. On average, the active fire season precipitation was very low in year 2003, 2007, 2008, 2012 and 2014 (Figure 2(a)). The total precipitation during active fire season was only 11% of the total annual precipitation during the 15 years, which was comparatively lower than total pre-monsoon precipitation (12.5%) of Nepal (Government of Nepal, 2015). In fact, the trend of total average precipitation during active fire season showed decreasing order (Figure 2(b)), indicating long precipitation-free intervals with low moisture in the fuel of forest provides a favorable environment for burning.

Our research findings are consistent with the findings of Lafon and Quiring (2012), which indicated that the precipitation regime with long precipitation-free intervals would generate more days per year that favors burning. A study done on precipitation trend in Kerela, India showed that the record of precipitations vary according to month, season and days (Krishnakumar, 2009). The total average precipitation and precipitation days were found to have decreasing trends in China (Song et al., 2011). A similar study was done in India, showed that there was decreasing trend of precipitation in the long term (Kumar et al., 2010). The findings of these past studies are consistent with our findings.

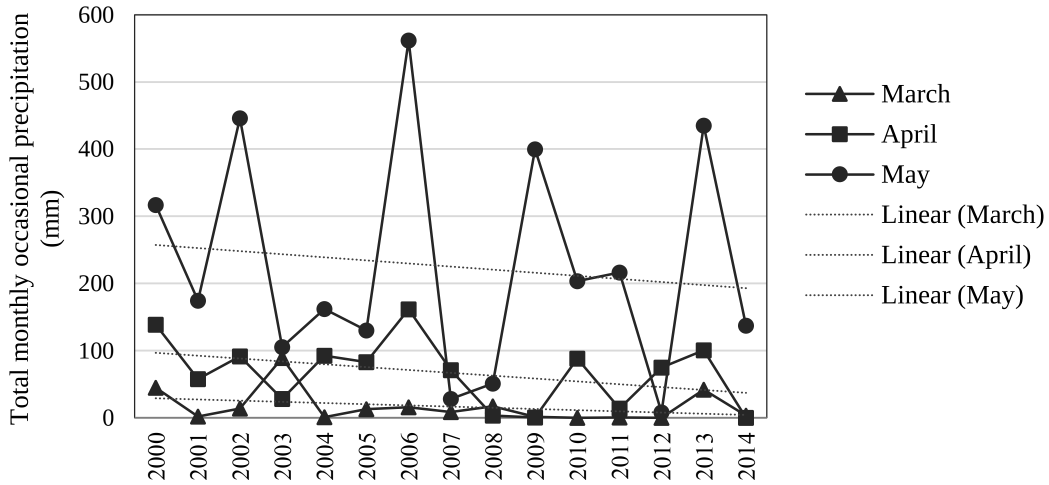

Figure 2(a). Status of precipitation in active fire season

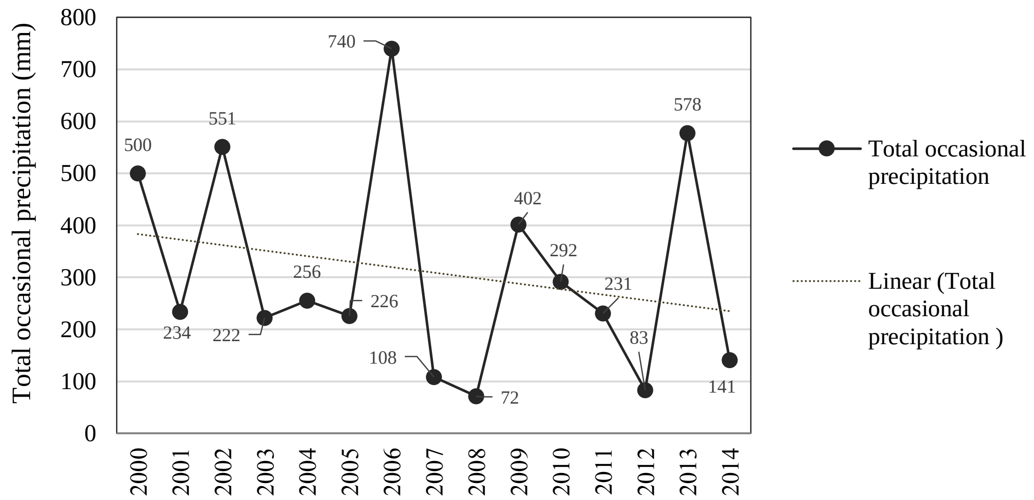

Figure 2(b). Trends of total precipitation in active fire season

3.2 Trends of forest fire incidence and burnt area

The incidence of wildfire varied widely during the active fire season (Figure 3). The highest numbers of wildfires were recorded in April of 2003, 2005, 2009, 2010 and 2012, while the lowest records were found in March and May. The highest coverage of burnt areas were found in years 2005, 2009, 2010, 2012 and 2014. The number of wildfires and burnt areas showed an increasing trend. In total, 1,472 wildfires and 4615.28 ha of forest area burnt were recorded in the active fire season in the 15 years, which constitutes 82.5% of total annual wildfires and burnt area. The number of wildfires and burnt areas increased annually. The highest number of wildfires and burnt areas were recorded in April. The finding was similar with the findings of Srivastava and Garg (2013), which also showed the higher incidences of wildfires in March and April in India due to the long spell of dryness and increased wildfire incidence caused by the reduction of precipitation. Moreover, extreme wildfire events are globally distributed across all flammable biomes and are strongly associated with extreme fire weather conditions (Bowman et al., 2017).

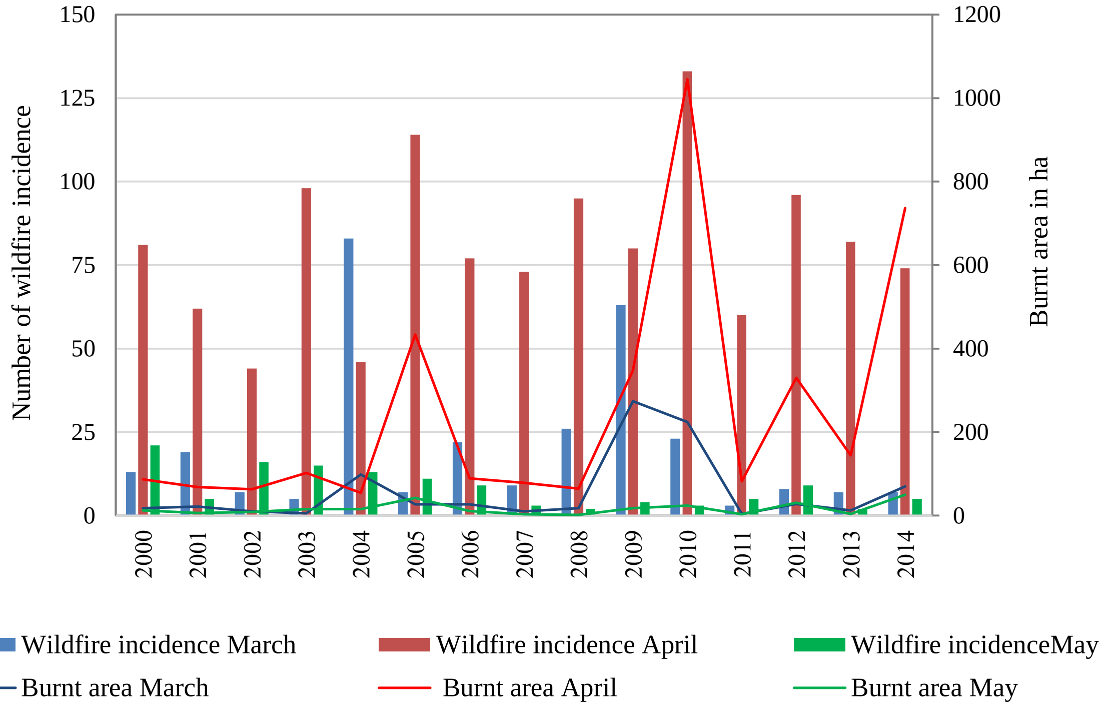

Figure 3. Trends of forest fire incidence and burnt area

3.3 Descriptive analysis of precipitation, wildfire incidence and burnt area

The highest mean occasional precipitation (about 225 mm) was recorded in May while the lowest (nearly 17 mm) observed in March. The highest mean values of wildfires and burnt areas were 81 fires and 248 ha respectively in April. The lowest mean values of wildfires and burnt area were 8 fires and 16.26 ha, respectively that occurred in May (Table 1). The variation of these parameters indicated the instability of occasional precipitation pattern and wildfire behavior.

Table 1. Description of precipitation, wildfire incidence and burnt area

Variables	Months	Mean	Std. Deviation	Std. Error	Minimum	Maximum
Precipitation	March	17.00	24.48	6.32	0	89
	April	67.00	49.73	12.84	0	162
	May	225.00	169.02	43.64	8	562
Number of wildfire incidence	March	20.13	5.92	22.94	83	3
	April	81.00	6.18	23.94	133	44
	May	8.20	1.51	5.87	21	2

Table 1. Description of precipitation, wildfire incidence and burnt area (cont.)

Variables	Months	Mean	Std. Deviation	Std. Error	Minimum	Maximum
Burnt area	March	56.46	21.36	82.74	274	4
	April	248.46	75.68	293.13	1045	55
	May	16.26	3.79	14.68	50	1

3.4 Relationship between precipitation with wildfire incidence and burnt area

The regression equation was $y = -0.0691x + 43.56$, which was derived between monthly occasional precipitation and wildfire incidence. In this equation, y indicates number of wildfires and x denotes monthly occasional precipitation of active fire season. Similar equation like $y_1 = -0.2859x_1 + 136.47$ was derived between annual average precipitation and burnt area, where y_1 is burnt area and x_1 stands for monthly occasional precipitation of active fire season. The r^2 values were 0.0617 and 0.0360 of wildfire incidence and burnt area (Figure 4(a) and 4(b)). These values showed the weak and negative relationship between occasional precipitation and wildfire incidence (Figure 4(a)). A similar relation was found between occasional precipitation and burnt area in active fire season (Figure 4(b)).

A t-test was conducted to examine the correlation between occasional precipitation and wildfire incidence and burnt area in active fire season. The p values for the estimated coefficients of occasional precipitation were 0.000 and 0.001 respectively (Table 2), indicating that precipitation was significantly correlated with the wildfire incidence and burnt area.

Table 2. Relationship equation values

Relations	t-test (P-value)	
	constant	Slope
Precipitation and fire occurrence	0.000	0.000
Precipitation and burnt area	0.001	0.001

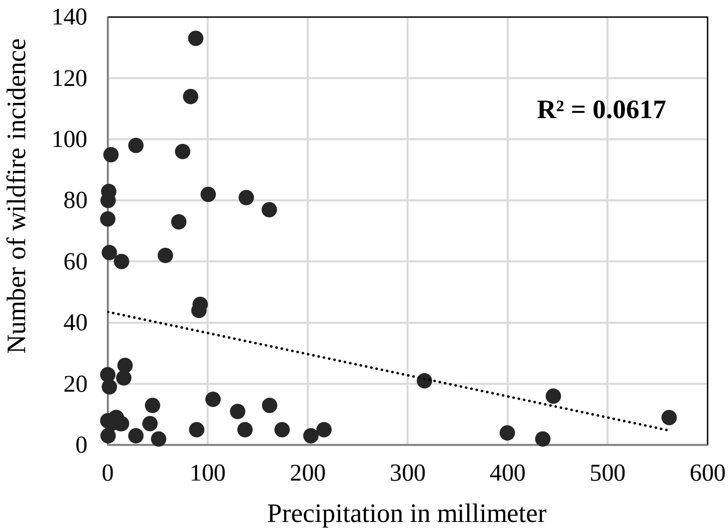

Figure 4(a). Relationship between precipitation and wildfire occurrence

The correlation between climatic factor (precipitation) and wildfire activities, like incidence and burnt area, indicated the significant effect of occasional precipitation on wildfire incidence and burnt area. This is consistent with the findings of Chen et al. (2014), which had indicated significant relationship between occasional precipitation and wildfire activities in the five eco-regions of Yunnan in China. Moreover, (Ponomarev et al., 2016) showed significant correlations were found between forest fires, burned areas and precipitation in the Siberian Larch Forest. Similar results were found by other authors like Khanal (2015), Good et al. (2008) and Littell et al. (2009) which indicated strong relationship between climatic variables and number of wildfires and area burned.

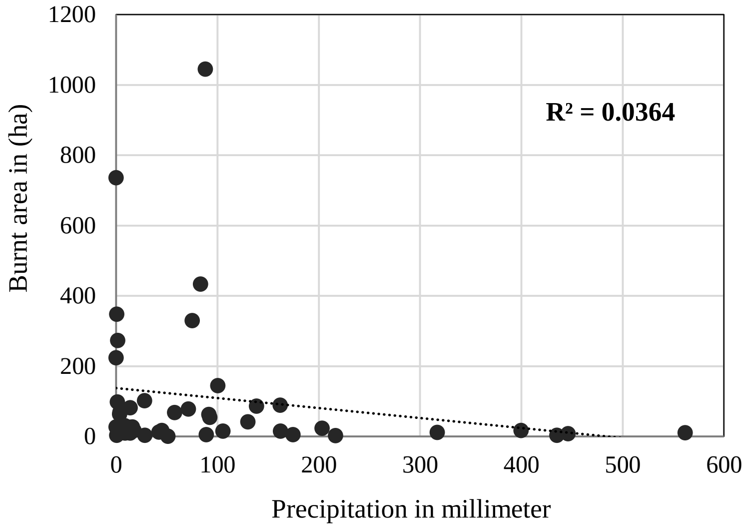

Figure 4(b). Relationship between precipitation and burnt area

4. CONCLUSIONS

The occasional precipitation was found to be the highest in March and lowest in April. The lowest occasional average precipitation showed decreasing trends in active fire season over 15 years period. The number of wildfires and burnt areas showed increasing trends over the same period. The highest numbers of wildfires were noticed in April of 2003, 2005, 2009, 2010 and 2012. There was a significant correlation between precipitation and wildfire activities (viz., number of wildfires and forest burnt area). The occasional precipitation variable affects the wildfire activities in the study area. The findings can be useful to both the policy makers and local forest managers for developing pre-fire alert system, preparedness for fire control and mitigation, and managing wildfires in the field.

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