FOREST FIRE MONITORING USING GIS: CASE STUDY OF MT. KENYA FOREST RESERVE

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ABSTRACT

The objective of this study was to assess between actual and modelled burned area accuracy, differences in fire spread and behaviour through the simulation of recent forest fires that affected the Mt Kenya Forest Reserve. The research analyzed differences between the actual and modelled fire predictions for two separate fires that occurred within the Mt Kenya Forest Reserve in March, 2015 at Irangi and March, 2012 at Chogoria forest stations. FlamMap minimum travel time (MTT) fire modelling software was used to compare spatial characteristics (fireline intensity and spread rate) of fires between the actual and the modelled fires. Comparative analysis between the actual and simulated fire area showed a relatively good agreement. The fire model provided a better understanding of the differences in fire growth and behaviour predictions over heterogeneous fuel landscapes, complex topography and changing weather conditions.

Keywords: FlamMap minimum travel time, Fireline intensity, spread rate, Sorensen coefficient and correlation.

INTRODUCTION

Forest communities are characterized by complex interactions between the woody and herbaceous flora, fauna, soils and other physical factors (Barnes *et.al.*, 1980). Forests are the protectors of earth's ecological balance. Unfortunately, most of the forest fires are usually detected when they have already spread over vast areas, making their control and suppression a nightmare. The result is devastating loss and irreparable damage to the environment and atmosphere (30% of carbon dioxide (CO_2) in the atmosphere comes from forest fires), in addition to irreparable damage to the ecology.

After the devastating fire seasons that affected Mediterranean Europe and other countries, the demand for models and tools for supporting forest fire spread monitoring and prediction has risen in recent years (Ager *et al.*, 2011; Salis *et al.*,2014; Schmuck *et al.,* 2014.) Fire modelling provides an analytical framework to characterize and predict fire spread and behaviour in diverse and complex fire environments (Van Wagtendonk, 1996; Stephens, 1998).Many fire modelling software's such as FARSITE (Finney, 1998) , NEXUS (Scott, 1999) , SPREAD (Mendes-Lopes and Aguas, 2000), FlamMap (Finney, 2006), FSIM (Finney *et al.*, 2011), Behave Plus (Andrews, 2007), ForeFire (Balbi *et al.*, 2009) and Fire and Fuels Extension to the Forest Vegetation Simulator- FVS-FFE (Rebain, 2010) have been developed over the years to help in wild fire management. The fire modelling systems involve explicit spatio-temporal modelling of forest fire spread over large landscapes, often heterogeneous in terms of vegetation and topography, with changing weather conditions and variable fire duration (Keane *et al.,* 2004; Cui and Perera, 2008), at different resolutions and variable fire front time-step projections (Yang *et al.*,2008). Thus, it's not only difficult to develop and calibrate these models with the aim of accurately predicting fires, but also to validate them under different burning conditions (Trunfio, 2004). Comprehensive data on historical fire occurrence, spread and behaviour, as well as on local scale environmental conditions in the areas nearby the fire events which are commonly available in USA and Europe, are not usually available in other countries, such as Kenya. Therefore, applications in fire modelling can be affected by the relatively inadequate information on fuel types and their characteristics, weather conditions, topography and past fire incidences. Calibration and validation is an important component when working with models (Albini and Stocks, 1986). Overall, the accuracy of fire modelling systems depends on the three major factors (WenBin and Perera, 2008):

1.) The availability and quality of input data,
2.) The theoretical basis of the fire behaviour model and.
3.) The fire growth algorithm.

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Much of forestland fire planning and decision making is intrinsically spatial and requires calculation, display and analysis of potential fire spread and behaviour across large landscapes (Finney, 2003). Two widely used simulators have been developed in recent years in order to facilitate such tasks: FARSITE (Finney, 1998) and FlamMap (Finney, 2006). FlamMap software generates potential fire behaviour characteristics at varying resolution set by user for a single set of environmental conditions giving the possibility to saturate the landscape with thousand independent fires. FlamMap incorporates the minimum travel time (MTT) algorithm, which computes the fastest straight-line fire growth between cell corners and produces a minimal distortion to fire shapes because there are no limits on angles or distances for searching (Finney, 2002). The MTT algorithm replicates fire growth by the Huygen's Principle, where the fire edge growth and behaviour are a vector or wave front (Richards, 1990; Finney, 2002). FlamMap can be run from the project level up to large landscapes scales in three calculation modalities:

1) Individual pixel basic fire behaviour to generate outputs such as fire intensity (kWm-1), rate of spread (m min-1), flame length (m) and crown fire activity (class).
2) Minimum MTT based fire spread from individual fire or ignition line to generate outputs such as rate of spread, fire intensity and preferential flow paths (straight -line transects)
3) MTT based fire spread from multiple ignition sources to generate burn probabilities, conditional flame lengths (m) and fire sizes (ac). FlamMap outputs are mostly used for landscape scale fire behaviour analysis and to identifying hazardous fuel and topographic combinations, thus aiding forest fire managers in prioritization and assessment (Stratton, 2004).

There are several studies that used FlamMap in USA, Southern Europe and elsewhere for fire spread and behaviour modelling with different purposes. FlamMap has been used in several research studies for quantative forest fire risk and exposure assessment (Ager *et al.*,2007 ;2010;2012; Bar Massada *et al.,* 2009; Thompson *et al.,*2011, 2013a, b; 2015; Parks *et al*., 2012 2014a; Mitsopoulos *et al*., 2015; Alcasena et al., 2015).

When using FlamMap, the environmental conditions remain constant during modelling hence it will not simulate temporal variations in fire behaviour caused by weather and diurnal fluctuations nor will it display spatial variations caused by backing or flanking fire behaviour. The outputs of FlamMap software are a variety of vector and raster maps of potential fire behaviour characteristics and environmental conditions (Finney, 2002) over an entire landscape. These raster layers can be viewed in FlamMap or exported for use in any GIS environment. The FlamMap software also creates a variety of vector outputs specific to each modelling system within the application. Gridded wind vectors are produced whenever Wind Ninja is used within the application and information on spotting (tabular and shapefile format) are also created. The MTT creates MTT flow paths and MTT Arrival Contours (Finney, 2002).

This study's aim was to assess the modelled burned area accuracy and the differences in fire spread and behaviour simulation predictions using FlamMap MTT, through the simulation of recent forest fires that affected the Mt Kenya Forest Reserve. The results and the methodology can be used for addressing fire management and planning needs, and identifying areas where the fire simulator disagree in predicting fire spread and behaviour. The results are also expected to be useful calibration data set for the model developers.

MATERIALS AND METHODS

Study Area

Mt Kenya Forest Reserve (Figure 1) is located along Latitude 0' 10'S and longitude 37' 20'E. The mountain is situated in two Forest Conservancies and five forest management zones (KFS, 2010). Mt Kenya is an ancient extinct volcano, which during its period of activity (3.1-2.6 million years ago) is thought to have risen to 6,500 m. There are 12 remnant glaciers on the mountain, all receding rapidly, and four secondary peaks that sit at the head of the U-shaped glacial valleys. (UNESCO, 1997). Mount Kenya Forest Reserve falls within the larger Mt Kenya Ecosystem which represent one of the most important mountain ecosystems in the World (UNESCO, 1997).

Rainfall pattern is bimodal which ranges from 900mm in the north (lee ward side) to 2300 mm on the south eastern slopes (wind ward side) of the mountain with maximum rains falling during the months of March to June and October to November. The driest months are January and February with the windward side experiencing the strongest effects of the trade wind system. The diurnal temperature range in January and February may be as high as 200C (KFS, 2010).

Mt Kenya Ecosystem consists of basic and intermediate rocks (Sombroek *et al.*, 1982).

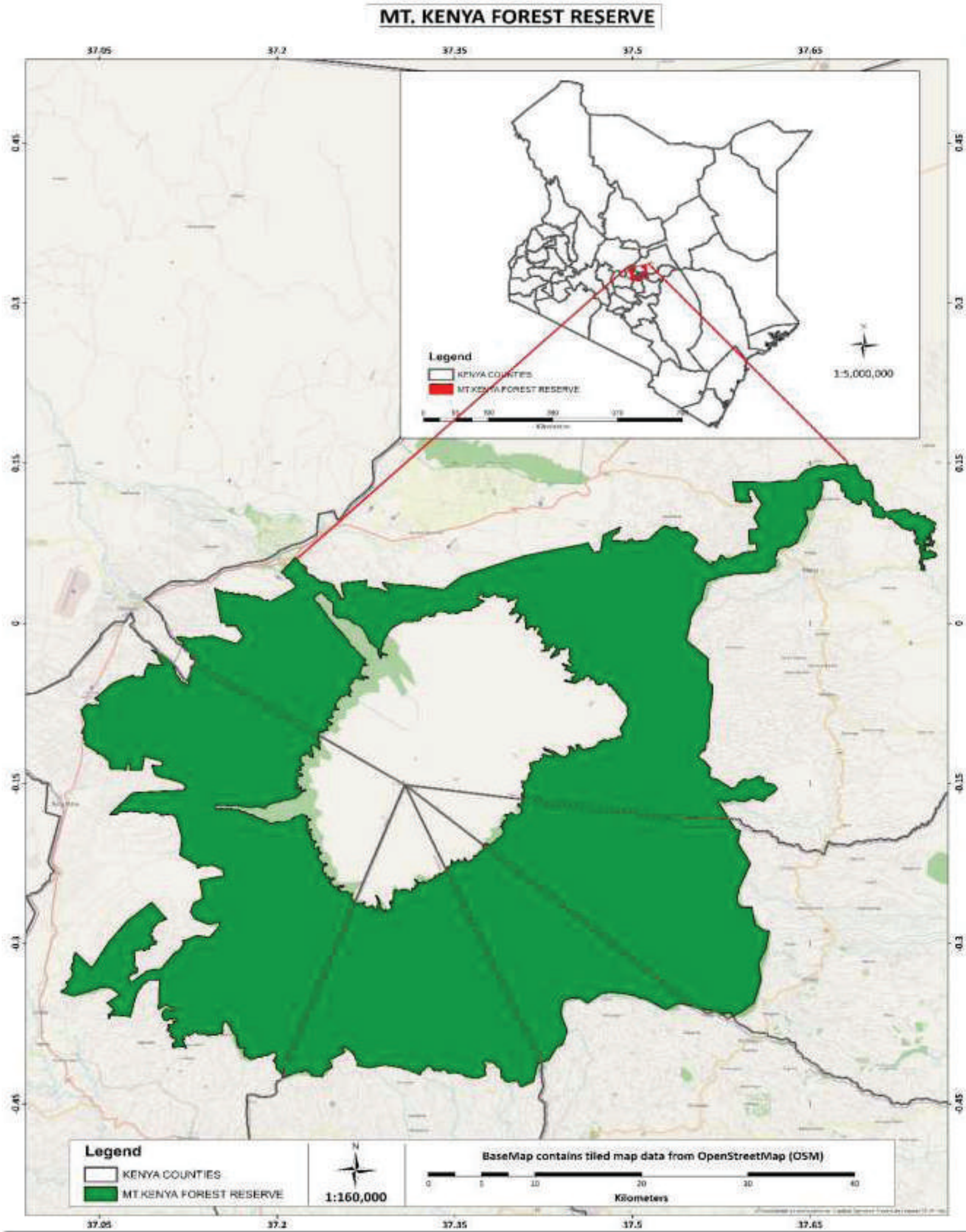

Figure 1. Study Area Map.

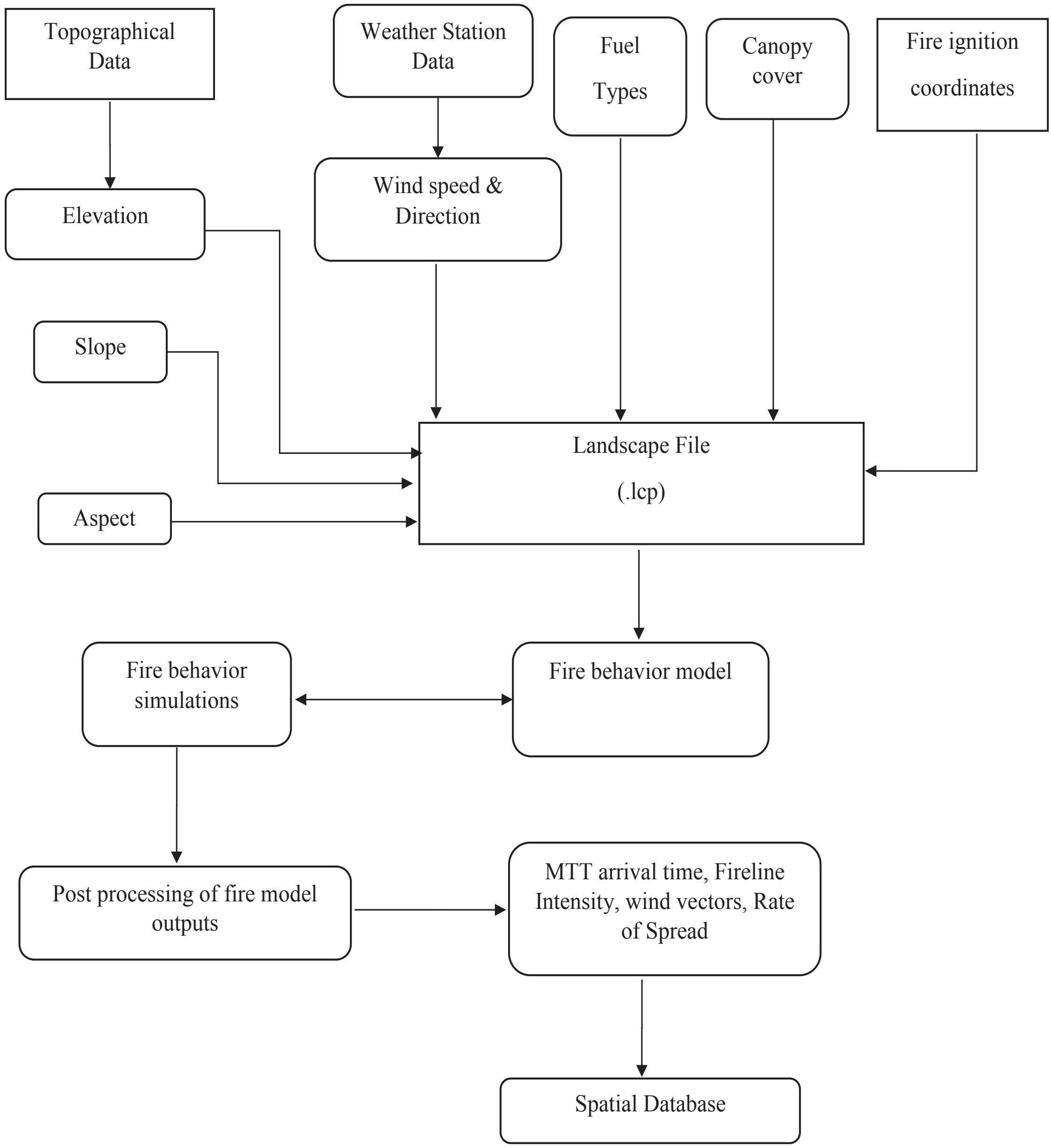

Figure 2. Methodological Framework.

Input Data

The FlamMap fire modelling software requires the same set of gridded geospatial input data files for fire simulation. Landscape characteristics, weather conditions and fuel types of the study area are presented in (Table I). Topography (i.e., elevation, slope and aspect) and fuel types were assembled into a 30 metres landscape grid file (LCP) of each case scenario in order to simulate fires at desired positions.

The digital elevation model (30 metres STRM) was used to generate the elevation, slope and aspect maps of the study area. Weather data was retrieved from Kenya Meteorological Department database. Constant weather conditions for the whole fire event (Finney, 2006), wind speed and wind direction observed during the active fire spread were used.

Data derived from KFS, 2019 concerning the fuel types within the Mt Kenya Forest was categorized into 8 classes namely; Multi-layered trees (broadleaved evergreen), Closed trees, Open trees (65-40% crown cover), Very open trees (40-15% crown cover), Closed to open woody vegetation (thicket), Closed shrubs, Open shrubs (45-40% crown cover) and Open low shrubs (65-40% crown cover). Areas within the Irangi forest station were predominantly classified as open trees (woodland) with 65-40 % crown cover whereas the Chogoria Forest station was classified as closed trees with the crown cover more than 70 – 60 %.

and Q_{ig} is the heat of pre-ignition (J/kg). Rothermel equation computes the steady-state rate of fire spread in the direction of maximum fire spread and assuming that wind and slope are aligned in this direction.

Fireline intensity (, kWm^{-1}) is determined from the fire rate of spread and fuel consumption using Byram's (1959) equation:

TABLE I – SUMMARY OF THE DATASETS USED IN THE STUDY.

Data	Source	Resolution and Characteristics
Weather Data	Kenya Meteorological Department (KMD)	Wind speed and direction.
Topography	STRM DEM, Downloaded from the USGS website (*earthexplorer.usgs.gov)*	30 metres spatial Resolution. Acquisition Date:2014.
Forest Boundary	Kenya Forest Service.	Boundary Shapefiles.
Canopy Cover & Fuel Type	Kenya Forest Service	Percentage of canopy and the fuel types shapefiles.
MODIS Burned Area collection	USGS	Burned area shapefiles.

Fire modelling

FlamMap (Finney, 2006) MTT algorithm was used to simulate Irangi and Chogoria fire incidences which occurred in separate dates. FlamMap makes independent fire behaviour calculations for each location of the raster landscape, independent of one another and weather and fuel moisture content data are held constant.

Fire growth simulations were conducted at 30 metres resolution. The adjustment factor for fire rate of spread was set at 1.0 for all simulations. No suppression efforts were considered in fire modelling due to inadequate information from Kenya Forest Service.

Three basic fire descriptors for each fire event: burned area, rate of spread and fireline intensity were calculated. The rate of spread in the Rothermel (1972) model can be defined as the ratio between the heat received by unburned fuel and the heat required to ignite the unburned fuel, and is calculated as:

$$ROS = \frac{I_R \times \varepsilon \times (1 \times \emptyset_W + \emptyset_S)}{\rho_b \times \epsilon \times Q_{ig}}$$

where ROS is the rate of spread (m /min), I_R is the reaction intensity (Js/m^2), ε is the propagating flux ratio, O_w is the wind factor,O_S is the slope factor, ρ_b is the fuel bed bulk density (kg/m^3),ϵ is the effective heating number,

$$FLI = H \times W_a \times ROS$$

where H is the net low heat of combustion (kJ/kg), W_a is the fuel consumed in the active flaming front (kg/m2), and is the linear rate of fire spread (m/s). It is assumed that the fire spreads by a sequence of ignitions, where the heat produced from the flaming zone of the fire provides sufficient energy to ignite the adjacent unburned fuels (Dimitrakopoulos and Dritsa, 2003). Burned area predicted were drawn from the conversion of the ROS raster layer to a vector layer.

Statistical and graphical analysis

The accuracy in simulated burned area was assessed by calculating Sorensen coefficient (*SC*) (Legendre and Legendre, 1998) and Jaccard Similarity coefficient (S_j) (Jaccard, 1912), which can range from 0 to 1.0. The closer to 1 shows more similarity between the data sets. The values were calculated as follows;

$$SC = \frac{2a}{2a + b + c}$$

Where; a is the number of cells coded as burned for both actual and simulated fires, b is the number of cells coded as burned in the simulation and unburned in the actual fire and c is the number of cells coded as unburned in the simulation and burned in the actual fire. The *SC* is an indicator of the exclusive association between the burned areas (actual and simulated). The higher the SC value, the higher the accuracy in burned area estimates.

The S_j Values were calculated as follows;

$$S_j = \frac{a}{a+b+c}$$

RESULTS

Burned Area prediction accuracy

Overall, the FlamMap MTT showed good agreement in predicting the actual fire area, with $0.55 \geq SC \leq 0.69$ and $0.38 \geq S_j \leq 0.53$ (Table III). In both cases (Irangi and Chogoria), the model overestimated the burned area in comparison with the actual fire derived from MODIS burn area collection.

The actual burned area of Irangi was 115.41 Ha; the MTT simulations yielded burned area of 153.10 Ha hence an overestimation in the area by 32.66%. For Chogoria, the

TABLE II- LANDSCAPE CHARACTERISTICS, FIRE WEATHER CONDITIONS AND INPUTS USED FOR THE FIRE.

	Irangi forest station.	**Chogoria Forest station**
Location	325793, 9971454 WGS 84 UTM 37S	329130, 9980520 WGS 84 UTM 37S
Topography	Elevation (m.a.s.l): 1459-5184 Slope (^{0}): 0-73 Aspect (^{0}): 0-359	Elevation (m.a.s.l): 1459-5184 Slope (^{0}): 0-73 Aspect (^{0}): 0-359
Fire Date(dd/mm/yyyy)	1/3/2015	14/3/2012
Fire suppression Date(dd/mm/yyyy)	3/3/2015	26/3/2012
Burned Area	115.41 Ha	500.96 Ha
Wind speed	22 mph	10 mph
Wind Direction	36^0	Downhill Direction 80^0
Rain (mm)	0	0
Simulation Resolution	30 metres	30 metres
Cause of fire	Suspected arson attack	Suspected poachers of small game.

TABLE III – EVALUATION OF THE FLAMMAP MTT MODEL FOR THE TWO CASE STUDIES.

Case Study	Fire growth Model	SC	S_j	a (Ha)	b (Ha)	C (Ha)	Actual Burned Area (Ha)	Simulated burned area (Ha)	% ± in simulated burned area
Irangi forest station	**MTT**	0.69	0.53	93.12	59.98	22.29	115.41	153.10	+32.66
Chogoria forest station	**MTT**	0.55	0.38	303.81	295.28	197.15	500.96	599.09	+19.59

Where: SC = Sorensen coefficient value, S_j = Jaccard Similarity coefficient, a =Area burned agreement, b = Area Overestimation, c =Area Underestimation

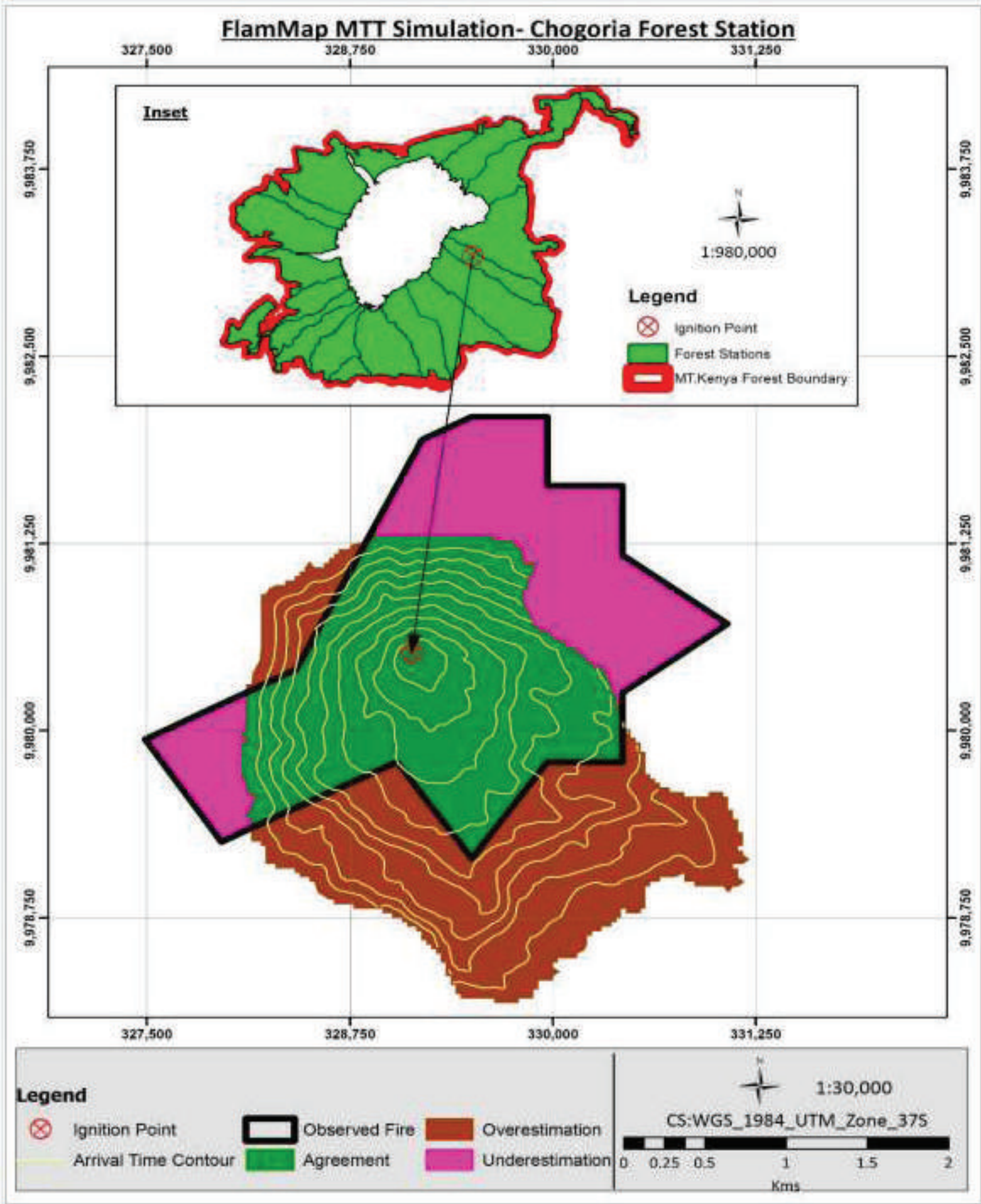

Figure 3. Map showing area agreement, overestimation and underestimation derived from FlamMap MTT simulation – Chogoria Forest Station.

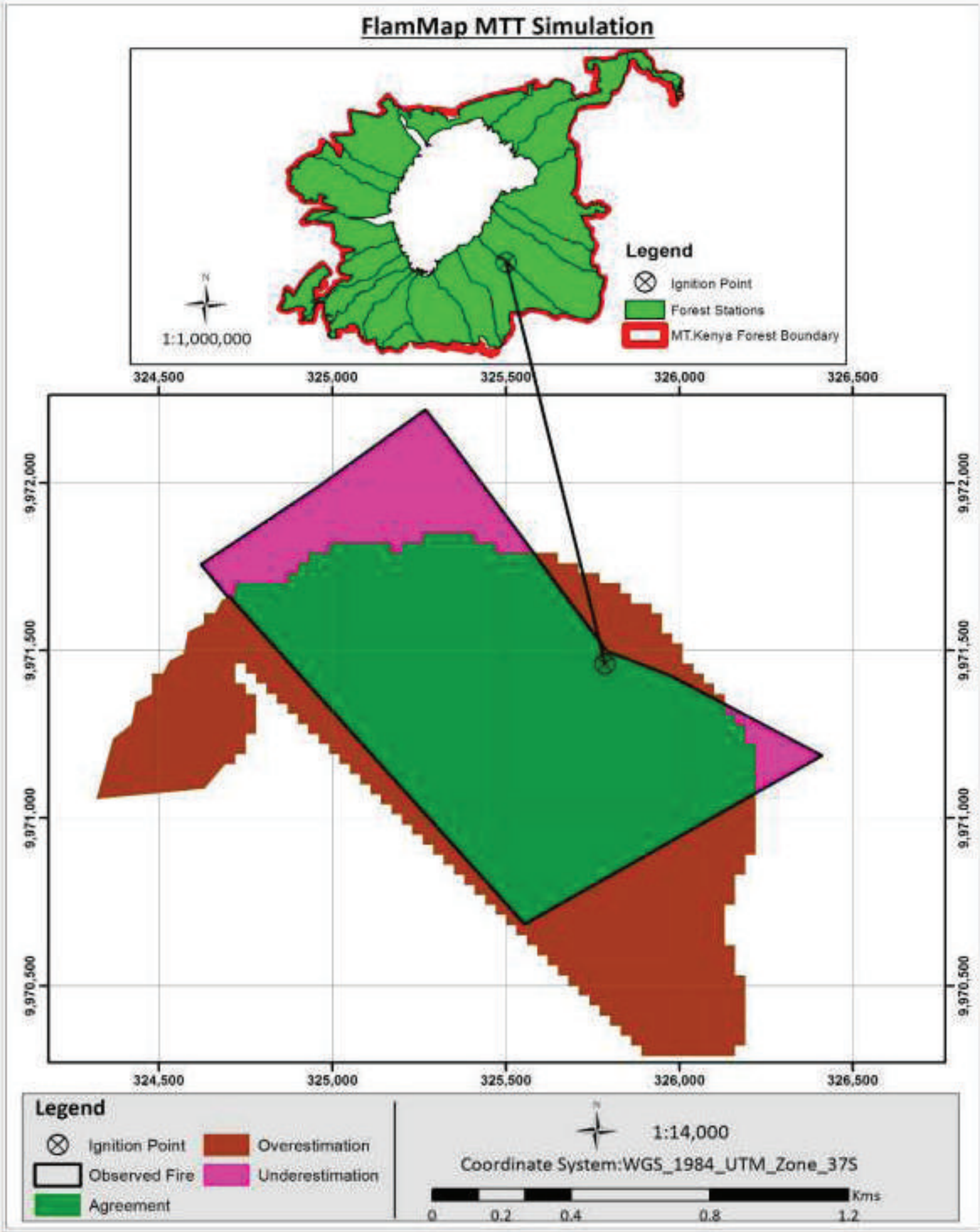

Figure 4. Map showing area agreement, overestimation and underestimation derived from FlamMap MTT simulation – Irangi Forest Station.

actual burned area was 500.96 Ha; the MTT simulations yielded burned area of 599.09 Ha hence an overestimation in the area by 19.59%.

In both cases (Irangi and Chogoria) the Sorensen coefficient (*SC*) is favorably high and tending to 1 unlike the Jaccard Similarity coefficient (S_j) which is relatively low. The closer the computed values get to 1 the more similar and correlation there is between the data sets.

Fireline Intensity and Rate of Spread

For Irangi forest section (Figure 5), the model yielded FLI values of 1390 kW/m (High) and 43 kW/m (Low). The corresponding values for Chogoria were 4625 kW/m and

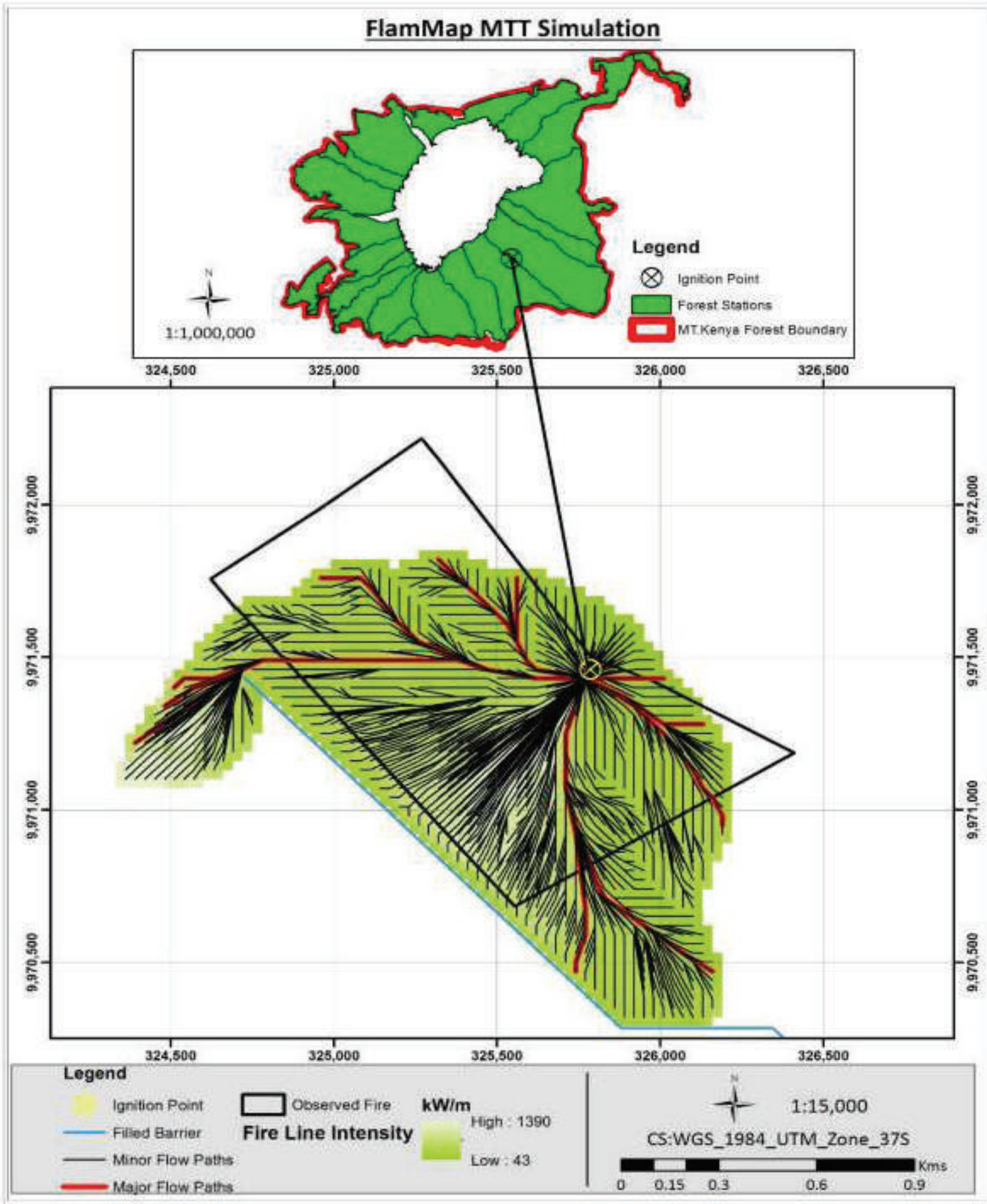

Figure 5. Fireline Intensity map -Irangi Forest Station.

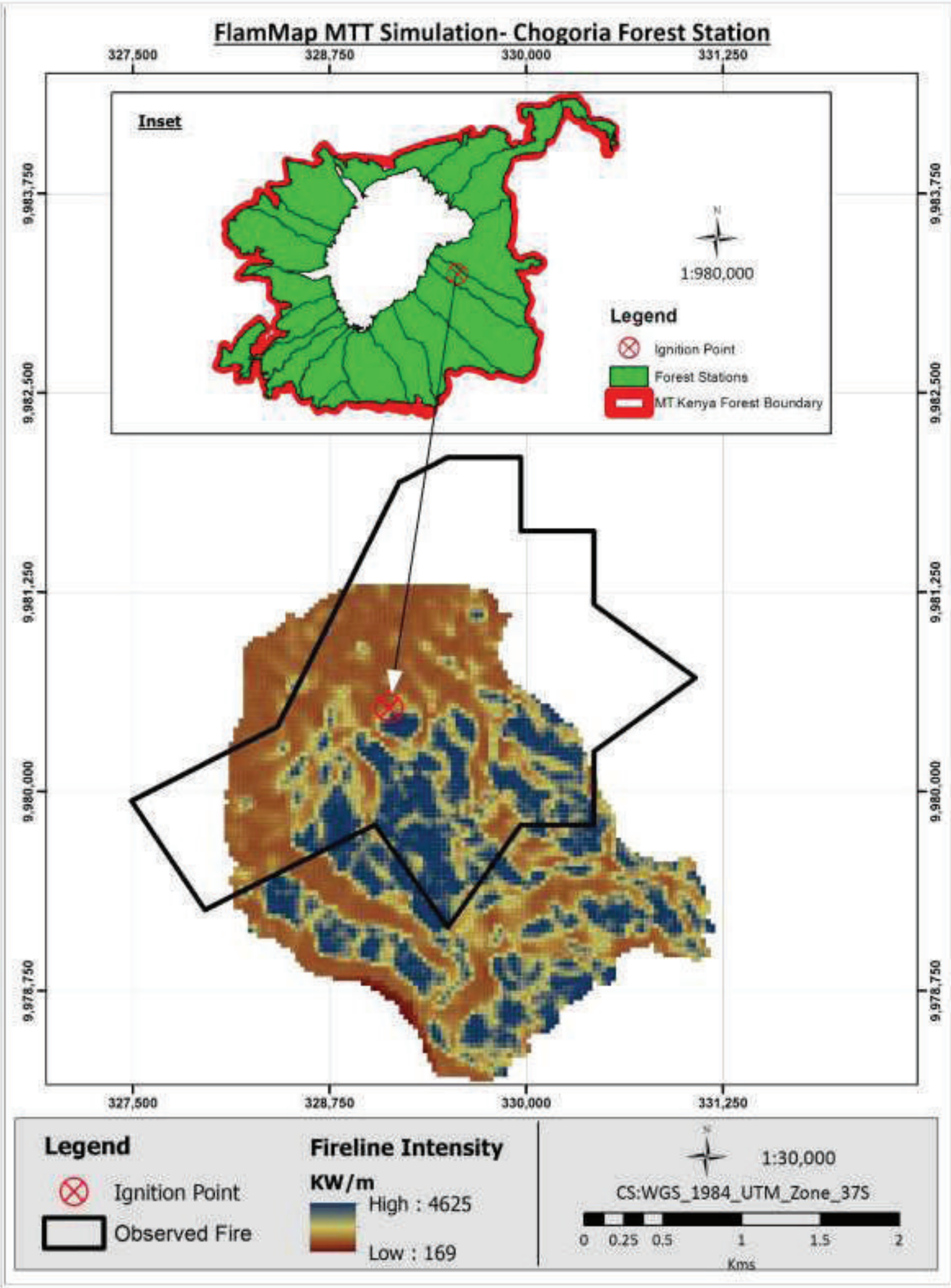

Figure 6. Fireline Intensity map - Chogoria Forest Station.

169 kW/m (Figure 6).

For the rate of spread, higher values were obtained from the Irangi Forest station (high values of 242 m/min and low values of 0 m/min) whereby the fire burnt out as a result of coming into contact with a filled barrier (river) (Figure 7) compared to Chogoria Forest station with (97 m/min for the high values and low values of 5 m/min) (Figure 8).

FlamMap (Finney, 2006), can incorporate barriers into MTT analyses. Barriers can either be filled or unfilled. In (Figure 7), a river was used as a filled barrier. The fire flanks along the filled barrier to the North and then continues spreading to the West before it burnt out. In (Figure 8), no barrier was incorporated into the model. No

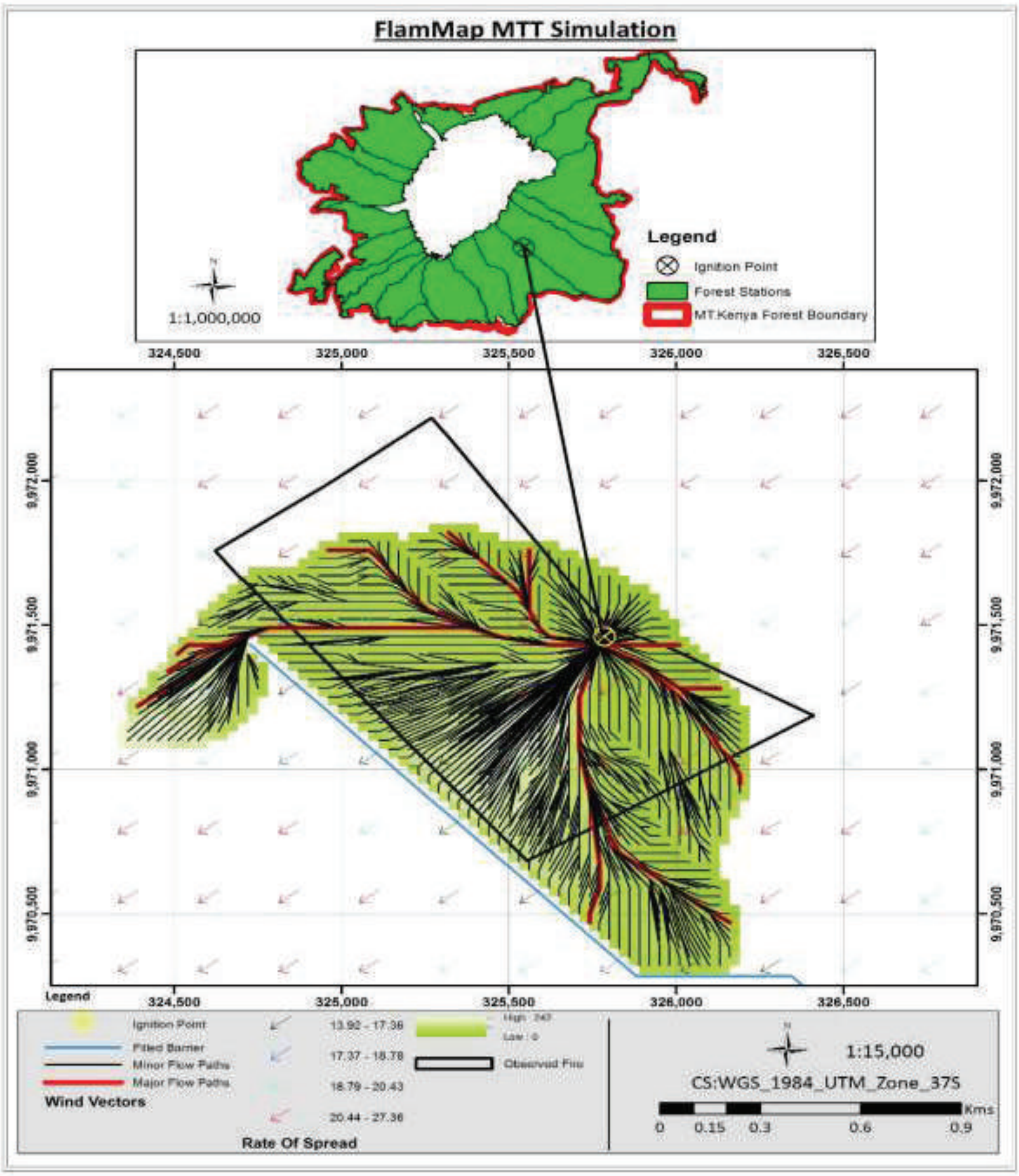

Figure 7. Rate of Spread Map – Irangi Forest Station.

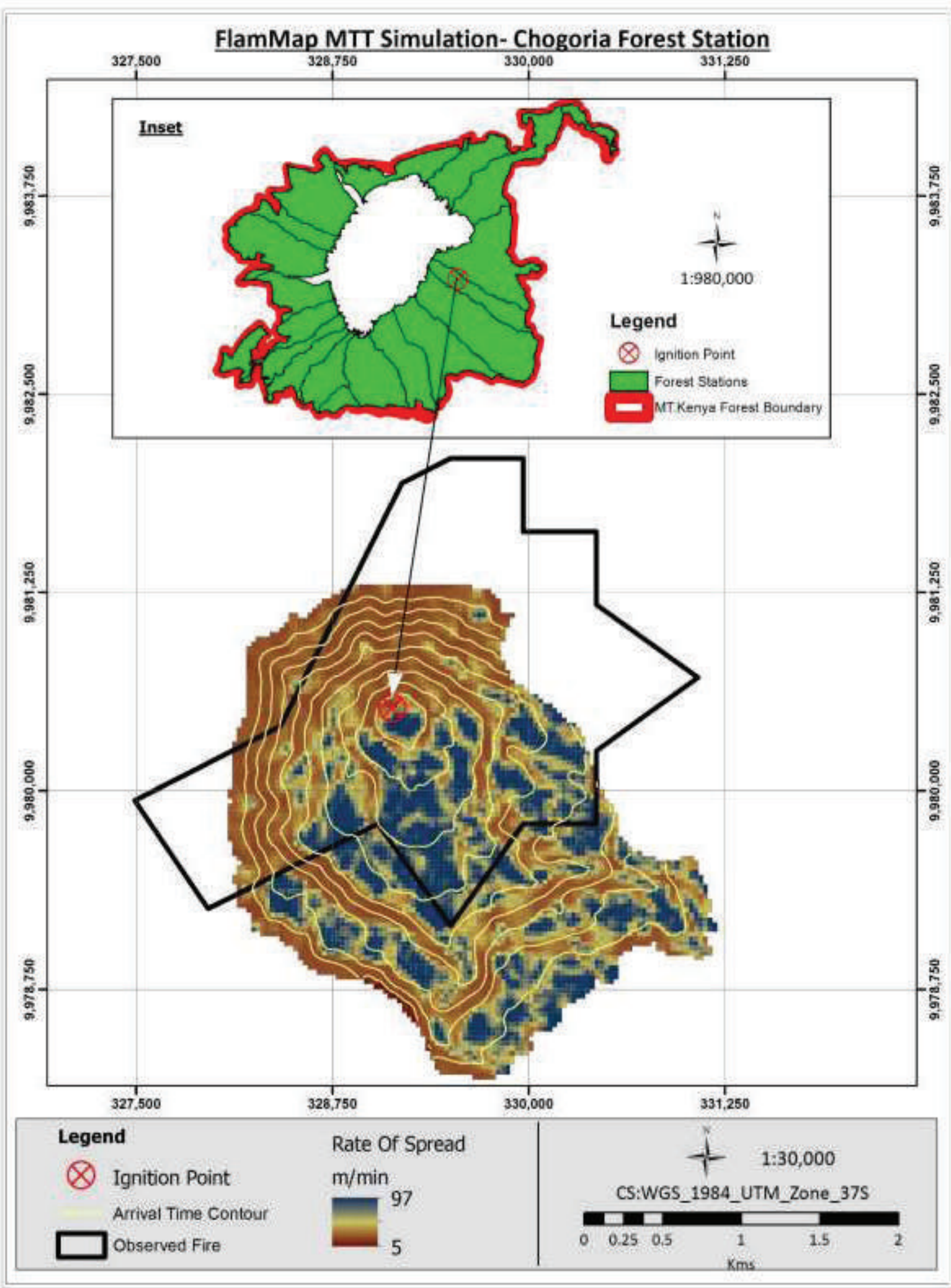

Figure 8. Rate of Spread Map – Chogoria Forest Station.

suppression efforts were considered in the fire modelling due to lack of accurate information.

DISCUSSIONS AND CONCLUSIONS

A variety of software can nowadays support fire management helping to reduce uncertainty for fire prevention and suppression. The numerous issues and limitations with the current fire modelling software such as inadequate and inaccurate input data needs to be addressed in order to consider a broad array of fire management problems in different areas (Ager *et al.*, 2011). Calibration of fire models with empirical data and sensitivity analysis should accompany all modelling efforts to help ensure appropriate application of the modelling tools (Arca *et al*., 2007; Jahdi *et al*., 2015).

In this study, fire growth and behaviour patterns across varying landscape using FlamMap MTT were compared to the actual. The FlamMap MTT showed reasonable results for the Irangi and Chogoria fires. The over prediction in the fire area simulations may reflect three factors:

1. The Rothermel Model which is incorporated into the FlamMap Model may over predict the rates of spread for the fuel type used.
2. Inaccuracy and uncertainty of the input data may result in incorrect fire propagation and behaviour values.
3. Inadequate information on fire suppression activities may cause over prediction in simulated areas.

The statistical evaluation of the performance of the FlamMap MTT simulator in terms of and is clearly shown for the two case studies (Table III). Regarding simulation of the fire events in the study area it showed that FlamMap MTT achieved favorable results. Further field studies of actual fire spread, fire area and behaviour are necessary in order to validate the outcomes of the fire behaviour simulations. Despite the differences between the actual and simulated fire area, the results from the study indicate that the potential for operational application of the model is promising particularly for forest fires management.

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