Quest Journals
Journal of Research in Environmental and Earth Sciences
Volume 8 ~ Issue 9 (2022) pp: 11-24
ISSN(Online) :2348-2532
www.questjournals.org

Research Paper

Simulation of bushfire propagation in northeast of Côte d'Ivoire by using FARSITE model and remote sensing

Kambiré SIE[1]*, Talnan Jean Honore COULIBALY[1], Naga COULIBALY[12], Lanciné Droh GONE[1], Inza COULIBALY[1], Koffi Claude Alain KOUADIO[3], Houebagnon Saint Jean Patrick COULIBALY[1], Charles Chuck MCHUGH[4], Kouadio Euclide N'GORAN[1], Souleyman CISSE[1], Issa CAMARA[1], Gaoussou SYLLA[1], Dramane YAO[1], Cédric INAGO[1], Matogoman CISSE[1], Adjoua Regine KOFFI[1], Henry Joel N'GUESSAN[1]

1 (Laboratoire de Géosciences et Environnement, Unité de Formation et de Recherche des Sciences et Gestion de l'Environnement, Université NANGUI ABROGOUA, Abidjan, 02 BP 801 Abidjan 02, Côte d'Ivoire)
2 (Unité de Formation et de Recherche d'Agricultures, Ressources Halieutiques et Agro-Industrie, Université de SAN-PEDRO, 01 BP 1800 San-Pedro 01, Côte d'Ivoire)
3 (Unité de Formation et de Recherche de Sciences Biologiques, Département de Mathématiques-Physique-Chimie, Université PELEFORO GON COULIBALY, BP 1328 Korhogo, Côte d'Ivoire)
4 (United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 U.S. Hwy 10 West, Missoula, Montana, USA)
**Corresponding author: SIE Kambiré*

Abstract
The damaging effects of bushfires in several countries have resulted in modeling efforts by the scientific community to understand these mechanisms of spread and behavior. This study uses FARSITE model to assess the risk of bushfire spread in Bounkani region. For this purpose, a digital elevation model (DEM) from an SRTM image and a LANDSAT image as well as meteorological data (temperature, relative humidity, wind speed and direction) were used. Five case studies covering the study area were simulated while randomly selecting the fire starting points. The results show that in this savannah area characterized by predominantly herbaceous fuel models, fire spread speed, flame length, fire intensity, heat quantity and power output can reach 43,71 m.min^{-1} (2,63 km.h^{-1}), 78 m, 29208, 79 kW.m^{-1}, 40867,22 kJ.m^{-2} et 2998,76 kJ.min^{-1} m^{-2} respectively. However, in savannah zones characterized by predominantly woody fuel models, fire spread speed, flame length, fire intensity, amount of heat, and power output can reach 3,82 m.min^{-1} (0,23 km.h^{-1}), 1,27 m, 438,80 kW.m^{-1}, 7595,98 kJ.m^{-2} et 686, 77 kJ.min^{-1} m^{-2}. Areas with a high predominance of herbaceous vegetation are those with a higher risk of fire spread. The results of this work are very interesting and would be useful as a decision support tool for bushfire management if improved.

***Keywords**: Fire behavior, GIS, Remote sensing, Bushfires, Simulation, Bounkani region, FARSITE*

***R**eceived 25 August, 2022; **R**evised 28 Sep., 2022; **A**ccepted 09 Sep., 2022 © The author(s) 2022.*
P**ublished with open access at **www.questjurnals.org

I. Introduction

Every year, bushfires destroy the African continent more than anywhere else on the globe [1]. In fact, Africa is even nicknamed the fire continent because of its recurrent savannah fires and the regression of its tropical forest [2]. Bushfires have become the most widespread major hazard in the world, particularly in West Africa. However, in spite of the advantages [3] that fire presents, it also presents numerous harmful effects to the ecosystems and the living environment [4,5]. In Côte d'Ivoire, fire is recognized as one of the main direct threats to the degradation of biodiversity and represents 3% [6]. Recent statistics from the National Committee for the Defense of the Forest and the Fight against Bushfires (CNDFB), show that between 1983 and 2004, 356 villages were burned, 122 human lives were lost and more than 89.5 million CFA francs were lost in property.

In addition, 120 people died in the flames of bushfires, 350 houses destroyed, 523,000 hectares of forests and crops ravaged between 2004 and 2014 [7].

For this reason, fire management is a major problem, even though the average area burned per fire has decreased in recent years [8,9] in these savannah areas. It is therefore imperative to better understand the functioning of bushfires in order to better organize fire management. The needs of managers in terms of modeling are multiple. This is why during the last decades, in order to improve the control and reduce the action time, several simulation models have been developed. Simulations are made to understand the real behavior of fire. Thus, the software used to simulate the propagation and behavior of fires have become decision support tools for forest managers and forest firefighters in several developed countries [10,11], because they present a fire propagation behavior similar to its actual occurrence [12]. Simulation modeling is an adequate tool for estimating risk when actual risk data are limited or unavailable. For planning firefighting strategies, it would help the fire management team to equip themselves to effectively control the fire using the direction of spread to minimize the damage.

Among these models, FARSITE (Fire Area Simulator) is the geospatial software widely used worldwide by engineering firms and managers for fire risk prediction in countries such as the United States, Canada, Brazil, and Australia [10,11,13]. The FARSITE simulator is effective in predicting fire spread using spatial and meteorological data. It requires spatial data obtained from GIS and remote sensing techniques [14,15] as well as meteorological data to simulate fire spread. Several works have demonstrated that FARSITE can be successfully adopted in the context of African savannahs as well [16,17,15]. The advantage of these models is that they have a very fast execution time, allowing managers or operators to have an immediate answer to their questions such as: Where will the fire be in one or two hours? How will it spread? How intense will it be? Which inhabitants will be threatened? The answers will help assess the characteristics of bushfires in relation to environmental variables for best management practices in tactical fire fighting and control, fire strategy and prevention, etc.

For this purpose, the Bounkani region was chosen as the study area. Indeed, the Bounkani region, located in the northeast of Cote d'Ivoire on the border of Ghana and Burkina Faso, is a predominantly agricultural and gold mining area where activities requiring the use of fire (cleaning of gold panning areas, subsistence agriculture and livestock, charcoal production, etc.) are diverse. Moreover, previous studies on fire history using GIS and remote sensing have already contributed greatly to the understanding of their spatio-temporal distribution and recurrence in northeastern Côte d'Ivoire, more precisely in the Bounkani region [9], and to the estimation of burned areas.

In this study, the aim is to show the utility of FARSITE model for predicting bushfire behavior in the Bounkani region in order to produce useful information for land managers and planners.

II. Material And Methods Of Work

2.1-Study cases

Firstly, it should be noted that agriculture remains the main activity that occupies the majority of the active population in the Bounkani region. The agriculture practiced is of the traditional type with rudimentary tools that inevitably require the use of fire [18]. Located in the extreme northeast of Côte d'Ivoire, between latitudes 9°56-8°55 North and longitudes 3°11-2°38 West, the region covers an area of 22,091 km² (Figure 1). Half of the region is occupied by the Comoé National Park with an area of 1,150,000 ha. The relief is heterogeneous. Indeed, it causes variability in wind trajectory and influences the distribution of vegetation according to altitude and fuel load. Geomorphology and terrain play an important role in the distribution and frequency of fires [19]. The hilly parts of the region are located to the northwest and southeast.

The region has a sub-Sudanese climate with two seasons [20]. Climate is a primary determinant of fire as it characterizes the state and nature of vegetation as well as weather conditions. The elements of climate directly or indirectly affect the fire regime and the nature of fire events.

Rainfall has both a direct and indirect effect on fire occurrence. Directly, it moistens the environment and prevents fires from developing. Indirectly, the amount of rainfall favors the development of combustible biomass (Figure 1). Bushfires, the subject of our study, are classified as surface fires. The vegetation found is essentially tree and shrub savannah with gallery forests. There are forest patches on the plateaus and gallery forests linked to the hydrographic network in the western part of the study area [21].

In addition, discussions and advice from Charles Mc Hugh, the lead developer of the FARSITE model's geospatial data layers, as well as model and data evaluation, allowed the simulation to be run on 05 study cases. This is because the Bounkani region is very large with varied vegetation types [22,18,23]. Therefore, the departments of Bouna, Doropo, Teheni, Nassian and the Comoé National Park were used as case studies to better understand and appreciate the simulation of fire behavior with the fire model.

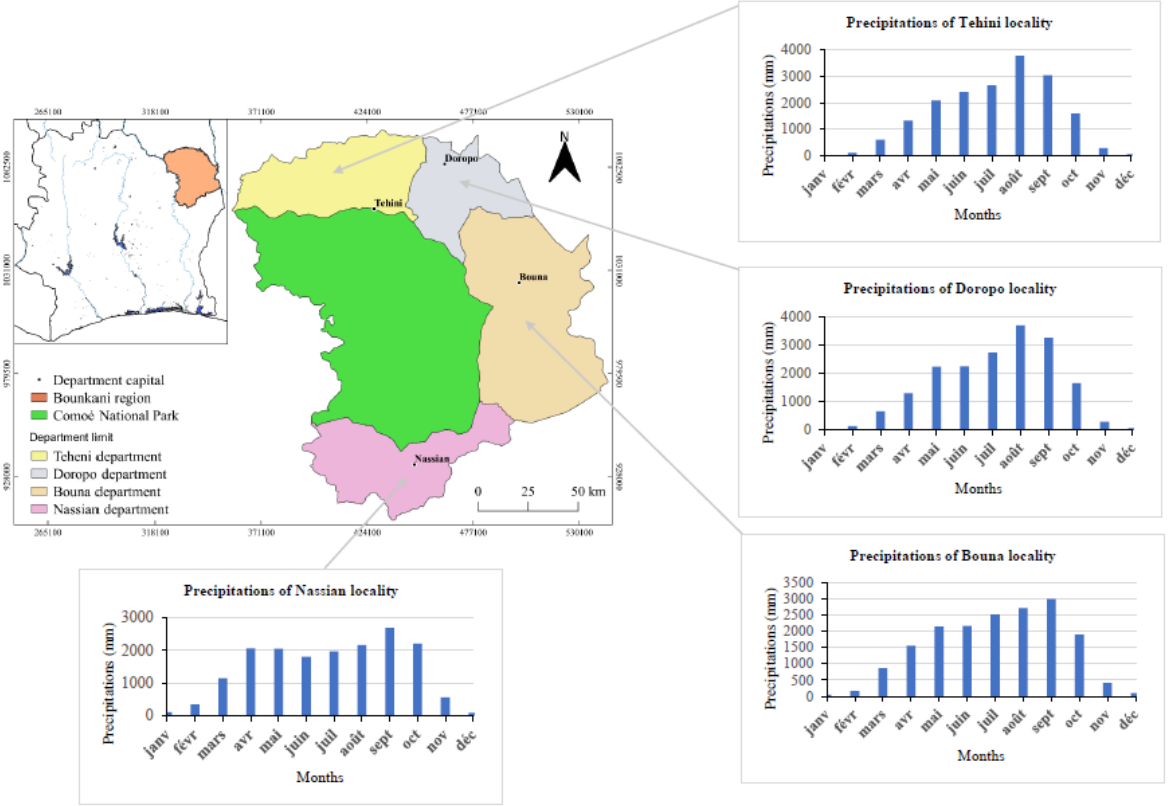


Figure 1: Localisation of area study

2.2. Presentation of the software tools

Tools used in our work consists of fire simulation software that requires remote sensing data generated in GIS software. QGIS 3.10 (Quantum Geographical Information Systems) is the open source GIS software used in this study to import and/or export the data to the other tools used in this work. For pre-processing and digital processing of satellite images, we used ENVI 5.3 (Environment for Visualizing Images).

Bushfires were simulated using the FARSITE version 4 vector deterministic fire model integrated into FlamMap version 6 since April 2021. This means that from now on FARSITE is no longer a stand-alone software but is rather available as an extension implemented in the fire mapping software FlamMap 6. However, nothing changes in its principle as well as its operation.

FARSITE is a spatial and temporal fire spread modeling tool developed by the US Forest Service (Missoula, Montana), initially to assist in the conduct of prescribed fires [10,24]. But its application has been increasingly extended to other areas of fire management. FARSITE allows a cartographic evaluation of fire spread, by calculating in stages the advance of a fire front across a landscape, using the Albini-Rothermel algorithm on fire behavior [25]. The two-dimensional graphical evaluation of the fire propagation is obtained by applying the Huygens principle that generates a series of ellipses from the initiated point, taking into account the heterogeneous conditions of the environment crossed by the fire [10,26].

The methodological approach of the FARSITE simulation model is based on the mathematical equation of Rothermel [26]. This makes it as widely applicable as possible.

This basis was provided by Frandsen [27] and Rothermel [26], who applied the principle of conservation of energy to a unit volume of fuel upstream of a fire advancing in a homogeneous fuel bed. Their analyses led to the following results:

$$R = \frac{I_{xig} + \int_{-\infty}^{0} (\frac{\partial I}{\partial Z})_{zc}\, dx}{\rho b_e * Q_{ig}} \quad (1)$$

R : Rate of propagation is almost stable (ft/mn with ft=0.3048m),

I_{xig} : Horizontal heat flux absorbed by a unit volume of fuel at the time of ignition (B.t.u/ft²/mn with B.t.u =1055.055J),

ρb_e: effective bulk density (amount of fuel per unit volume of fuel bed at the time of ignition before the fire), expressed as en lb/ft³ with lb=1/2. 20462 kg,

Q_{ig} : pre-ignition heat (amount of heat required to ignite a unit of fuel) expressed in B.t.u/lb,

$(\frac{\partial I}{\partial Z})_{zc}$: Vertical intensity gradient evaluated on a plane at a constant depth, (Btu/ft².mn), **zc** = constant depth of the fuel bed. The horizontal and vertical coordinates are respectively x et z.

2.3-Input data for fire simulation

FARSITE has specific data requirements for wildland fire simulation. Input data includes meteorological data such as temperature, precipitation, wind speed and direction, cloud cover, and GIS spatial layers. GIS layers include topography (elevation, slope, aspect) and vegetation (fuel model and canopy cover.)

For topography, a Shuttle Radar Topography Mission (SRTM) image, with a resolution of 30 m, was used to produce elevation, slope, and exposure maps of the 5 study cases using the spatial analysis tool in QGIS 3.10. For the vegetation or fuel GIS layer.

FARSITE, like most fire prediction or forecasting models, has been calibrated and validated in the United States in the different ecosystems of the Mediterranean basin [28]. Using FARSITE over areas different from those where the simulator was developed requires local calibration in order to produce reliable results. However, in the FARSITE model, standard fuel models or custom fuel models can be used. The custom fuel model is applied when the standard fuel model does not match the vegetation characteristics in a study area. This is true for our study cases.

As for the GIS vegetation layer required by FARSITE, remote sensing is the main tool used for the development of input layers, especially for large areas. For this purpose, a LANDSAT OLI image with a spatial resolution of 30 m covering the Bounkani region was subjected to an unsupervised classification that allowed the categorization of vegetation types (grasses, shrubs, trees) that are fuels with reference to existing standards [29]. The information provided by the Landsat image and through recognition on Google Earth pro, with reference to the classification of fuels of several authors [18,22,23,30] to highlight six classes of elements in our study area has see in Table II.

It should be remembered that the production of fuel models or vegetation types requires detailed knowledge of the characteristics of each vegetation model or fuel as this is the key parameter for any simulation activity with FARSITE [24,31]. Each fuel model includes the information recorded in the following Table I.

Tableau I: Properties of fuel types

Field	Definitions
FMNum	Fuel model number
FM Code	Fuel model code
1H, 10H, 100H, Live H, Live W	Live and dead fuel moisture content
FM Type	Fuel type " static " ou " dynamic ".
1HSAV, Live HSAV, Live WSAV	Surface to volume ratio
Depth	Depth of surface fuel
XtMoist	Moisture Extinction: amount of fuel moisture in the dead fuel above which fire propagation is not possible
DHt, LHt	Heat content in live and dead fuel
FM Name	Fuel moisture name

In this study, the values of total amount of live and dead fuel, the ratio of overstrength to volume and the depth of fuel obtained by [13] in tropical savannas of Brazil and also the values of extinction humidities [17] were chosen for the following reasons:

- The implementation of a customized fuel model with the characteristics of each fuel type requires significant resources for the detailed study of vegetation types,
- There is a similarity between the Brazilian savanna and the savanna of tropical Africa [32,33],
- The vegetation of our study area is identical to that of the study by Mbow [17] on the Senegalese savannah, who also used some humidity values from the study [16] on the South African savannah.

Tableau II : Summary of parameters used in the simulation

Study cases	Ignition point	Simulation time (h)	Numbers and type of Vegetations	Canopy cover (%)	Elevation (m)	Slope (°)	Aspect (°)
Doropo department	Long :1064745 Lat : 452990	11-18	14MCJ, 15SAV, 16SAR, 17FDS, 18FC, 19FG, 20SB, 21SH, PE, NB	0-90	168-695	0-6,20	0-360
Teheni deepartment	Long : 1073668 Lat : 401080						
Nassian department	Long :928422 Lat : 415683						
Bouna department	Long :974498 Lat : 437391						
Comoé national Park	Long : 1001325 Lat : 436359						

MCJ= Mosaic culture and fallow land; SAV= Shrub savannah; SAR= Tree savannah; FDS= Dense forest; FC=Clear forest ; FG=galery forest ; SB= Woodland savannah; SH=Grass savannah ; PE=Water area ; NB=Bare soil/Housing

For this simulation with the FARSITE simulator the units of the input variables chosen are in ENGLISH units for the FMD files. The spatial data in FARSITE are embedded in a single landscape file (extension LCP). The landscape file (.LCP) contains raster data that are obtained from a GIS for terrain and fuels or vegetation. All raster data is embedded in an ASCII grid format exported from QGIS.

In addition, the weather file (.WXS) is a mandatory ASCII text file for any FARSITE simulation. This file contains daily temperature and humidity observations as well as precipitation, describing a time stream of climate. The weather data used to run the simulation in the FARSITE simulator comes from the CHIRPS product completed with data from the NOAA National Climatic Data Center. These data were converted to ASCII text format before being entered into the FARSITE model.

After providing all the necessary data, the simulation was run with a runtime of 6 hours. The roads were used as a barrier for the fire when creating the fire growth and spread model.

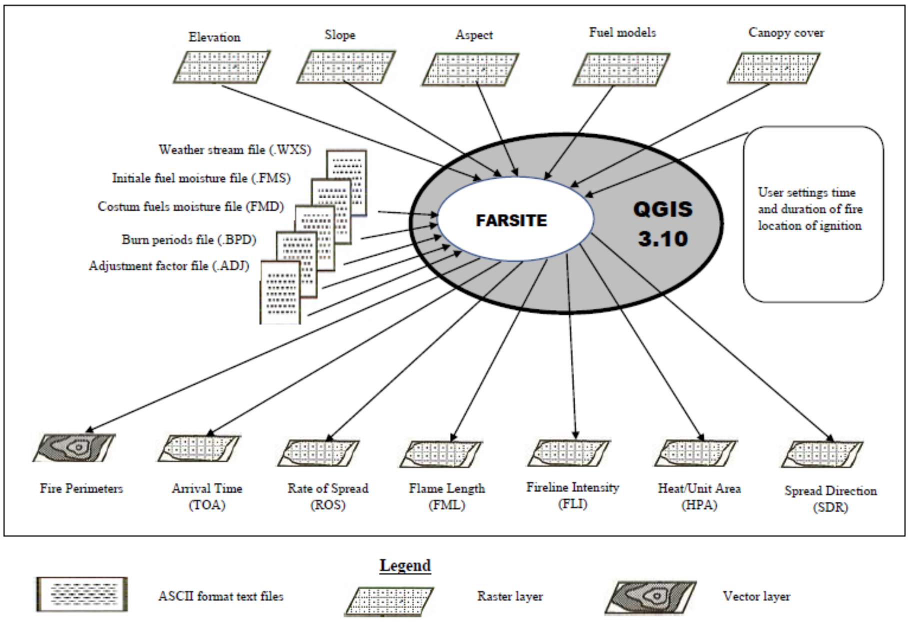


Figure 2 : Fire simulation methodological diagram

III. Results and discussion

3.1-Fire perimeters

The area burned by the fire was obtained from the fire perimeter vector file on the QGIS software. Figure 3 illustrates the extent of the simulated fire perimeter in the five (05) study cases, namely the department of Bouna, the department of Doropo, the department of Teheni, the department of Nassian and the Comoé National Park. The fire spread according to the type of fuel influenced in parallel by the slopes and winds after 1 hour of fire simulation. It should be noted that the simulated fire spread varied considerably in shape (Figure 3, 4, 5, 6, 7, 8, 9, 10) and size (Table III). First, the results show that in Bouna department, the fire spread through the savanna arboreum (SAR) and savannah grassland (SH) vegetations with a burned area of 4987.34 ha. Then, in the departments of Doropo and Teheni, the fire spread through the same types of vegetation of crop-fallow mosaic (MCJ), shrub savannah and gallery forest with a burnt area of 4034.58 and 3658.51 ha respectively. Then, in the department of Nassian, the fire spread through the vegetation of dense dry forest (FDS), tree savannah (SAR) and gallery forest (FG) with an area of 21.27 ha burned. Finally, the fire spread through the dense dry forest (FDS) and the wooded savannah (SAR) in Comoé National Park with a burnt area of 34.76 ha.

Tableaux III : Area burned during 7 hours of simulation in 5 study cases

	Burned areas (ha)				
Simulation time (h)	Doropo department	Teheni department	Nassian department	Bouna department	Comoé National Park
11:00	0	0	0,23	59,79	0,22
12:00	91,21	71,34	0,88	221,59	0,87
13:00	476,18	468,71	3,22	511,4	2,32
14:00	653,46	435,08	2,63	630,88	3,01
15:00	395,83	265,24	1,96	422,71	2,62
16:00	470,37	453,09	2,41	547,01	3,59
17:00	987,68	1030,27	5,13	1239,27	9,9
18:00	959,85	934,78	4,81	1354,69	12,23
Total	4034,58	3658,51	21,27	4987,34	34,76

From Table III, it can be seen that the fire took about 4 hours to burn nearly 1,500 ha, and another 3 hours to reach nearly 2,500 ha in Doropo Department. Then, in Bouna department, the fire took about 4 hours to burn nearly 1424 ha and another 3 hours to reach nearly 3564 ha. Then, in the department of Teheni, the fire took 4 hours to burn nearly 1241 ha and another 3 hours to reach nearly 2419 ha. Then again, in Nassian department, the fire took about 4 hours to burn nearly 9 ha and again about 3 hours to reach nearly 12 ha. Finally, in Comoé National Park, the fire took about 4 hours to burn nearly 9 ha and another 3 hours to reach nearly 26 ha.

According to Table III, it can be seen that from 11:00 to 14:00, i.e., after 3 hours of simulation time, the area covered by the fire decreased slightly and then increased again from 16:00 to 18:00, i.e., after 2 hours, in all five (05) study cases. In fact, in all the case studies, we notice that the contour of the fire does not have the same shapes and also the increase of the burned surface was not constant, because the local characteristics (topography, fuel, climate) determine a more or less important advance of the fire.

3.2. Time of arrival (hrs)

Figure 4 is a graphical representation of the fire fronts, displayed at 1 h intervals, produced by the simulation model, for the 5 case study fires. The results show that for a duration of 7 h predicted during initialization, the fire progression varies according to weather conditions and fuel characteristics. For the same time intervals, the distances traveled in the five (05) case studies are very similar in all directions. With the effect of wind, it can be observed for the same time steps, large distances are traveled in the wind direction, and short distances on the opposite side to the wind (Figure 4). Figure 4 shows that for the same time interval, fire propagation is very fast at certain periods in the presence of wind.

In general, as the duration increases, the fire progresses through the study areas. This affects the intensity or speed of fire spread as well as the rate of fire burn. In addition, the fire stops or is extinguished when it encounters an obstacle or barrier (natural/artificial) that corresponds to non-burnable fuels and therefore did not promote the spread of the fire.

3.3. Rate of spread (m.min^{-1})

Rate of spread, or speed of fire spread, depends on the type of fuel, the degree of humidity, but especially on the wind speed and the topography. The Rate of Spread gives general information about the effect of fuel and environmental conditions on fire behavior. In general, this speed is first very low at the beginning of the fire, and it becomes more and more considerable as can be seen in figure 5. The results (figure 5) show us that for the same time interval, the fire does not propagate in the same way over all the simulated areas. That is, the size and shape of the fire spread varies. Indeed, in the department of Bouna the rate of propagation varies from 0.00 to 30.80 m.min-1. Then in the department of Doropo, the rate of spread varies from 0.00 to 43.71 m.min^{-1}. Then the propagation rate varies from 0.00 to 39.18 m.min^{-1} in Teheni department. Then again, the propagation rate varies from 0.03 to 3.82 m.min^{-1} in the department of Nassian and finally, in Comoé National Park, the propagation rate varies from 0.18 to 3.58 m.min^{-1}.

In general, the results indicate that the departments of Doropo, Teheni and Bouna have the highest fire spread rates, with values of 43.71, 39.18 and 30.80 respectively. While the department of Nassian and the Comoé National Park have the lowest fire spread rates with values of 3.82 and 3.58 m.min-1. We can also note that the slopes in our study area are more or less low. That said, it has or has not a significant influence on the propagation speed. On the other hand, the presence of wind increases the propagation rate which then becomes moderate. This rate can be high when the wind speed increases.

3.4. Flame length (m)

Figure 6 shows the comparison of flame length or size according to the type of fuel or vegetation used. First, in Bouna Department, the results show that the flame length varies from 0.05 to 4.30 m, then in Doropo Department, the flame length varies from 0.03 to 8.78 m. Then, the results indicate in the department of Teheni that the length of the flame varies from 0.02 to 8.08, then again in the department of Nassian, the length of the flame varied from 0.05 to 1.27 m. And finally, in Comoé National Park, the length of the flame varied from 0.15 to 1.25 m.

In all five (05) study cases, the departments of Doropo and Teheni had the highest flame lengths of 8.78 and 8.08 m respectively during the 7-hour simulation, followed by the department of Bouna with a maximum value of 4.30 m. While Nassian Department and Comoé National Park showed the lowest flame lengths during the 7 hours of simulation time with a maximum value of 1.25 and 1.27 m respectively.

3.5. Fireline intensity (kW.m^{-1})

Fireline intensity shows similar characteristics to the flame length results (Figure 7). Note that the flame length depends only on the intensity of the fire line. Therefore, the longer the flame length, the higher the fireline intensity. The results of this study indicate that the intensity of the fire line varies from 0.37 to 6177.07 kW.m^{-1} in Bouna department. Then, in Doropo department, the intensity of the fireline varies from 0.09 to 29208.79 kW.m^{-1}. Then, in Teheni Department, the fireline intensity varies from 0.08 to 24360.23 kW.m^{-1}. Then again, in Nassian department, the intensity of the fire line varies from 0.33 to 438.80 kW.m^{-1}. Finally, in Comoé National Park, the intensity of the fireline varies from 4.44 to 419.96 kW.m^{-1}. In addition, in all five (05) study cases, the department of Doropo and Teheni revealed more intense fires with a value of 29208.79 and 24360.23 kW.m^{-1} respectively followed by the department of Bouna with a value of 6177.07 kW.m^{-1} after 7 hours of simulation. On the other hand, the lowest intensities were observed in Nassian department and Comoé National Park with a maximum value of 438.80 and 419.96 kW.m^{-1}.

3.6. Reaction intensity (kJ.min^{-1}m^{-2})

It is the power released by the fire per unit area. This power varies momentarily and its characteristics are related to those of the fire lines, with the only difference being that it varies per unit area. The maps below (Figure 8) present the reaction intensity in five case studies, namely Bouna Department, Doropo Department, Teheni Department, Nassian Department and Comoé National Park. The results revealed that in the department of Bouna, the intensity of reaction varies from 0,00 to 992,37 kJ.min^{-1} m^{-2}Then, in the department of Doropo, the intensity of reaction varies from 0,00 to 2998,76 kJ.min^{-1} m^{-2} then in Teheni department, the intensity of reaction varies 0,00 to 2960,21 kJ.min^{-1} m^{-2}. Then again, at the level of Nassian department, the reaction intensity varies from 13,93 to 653,34 kJ.min^{-1} m^{-2}. Finally, the reaction intensity varies from 66, 81 to 686, 77 kJ.min^{-1} m^{-2} in Comoé National Park after the 7 hours of simulation.

In all 5 simulation case studies, Doropo and Teheni departments show the highest reaction intensities with a value of 2998, 76 and 2960, 21 kJ.min^{-1}m^{-2} during 7 hours of simulations. On the other hand, the department of Bouna shows a weak reaction intensity of a value 992,37 kJ.min^{-1}m^{-2} followed by Nassian department and Comoé National Park revealed the lowest reaction intensities with a value of 686,77 and 653,34 kJ.min^{-1}m^{-2}.

3.7. Heat per area (kJ.m^{-2})

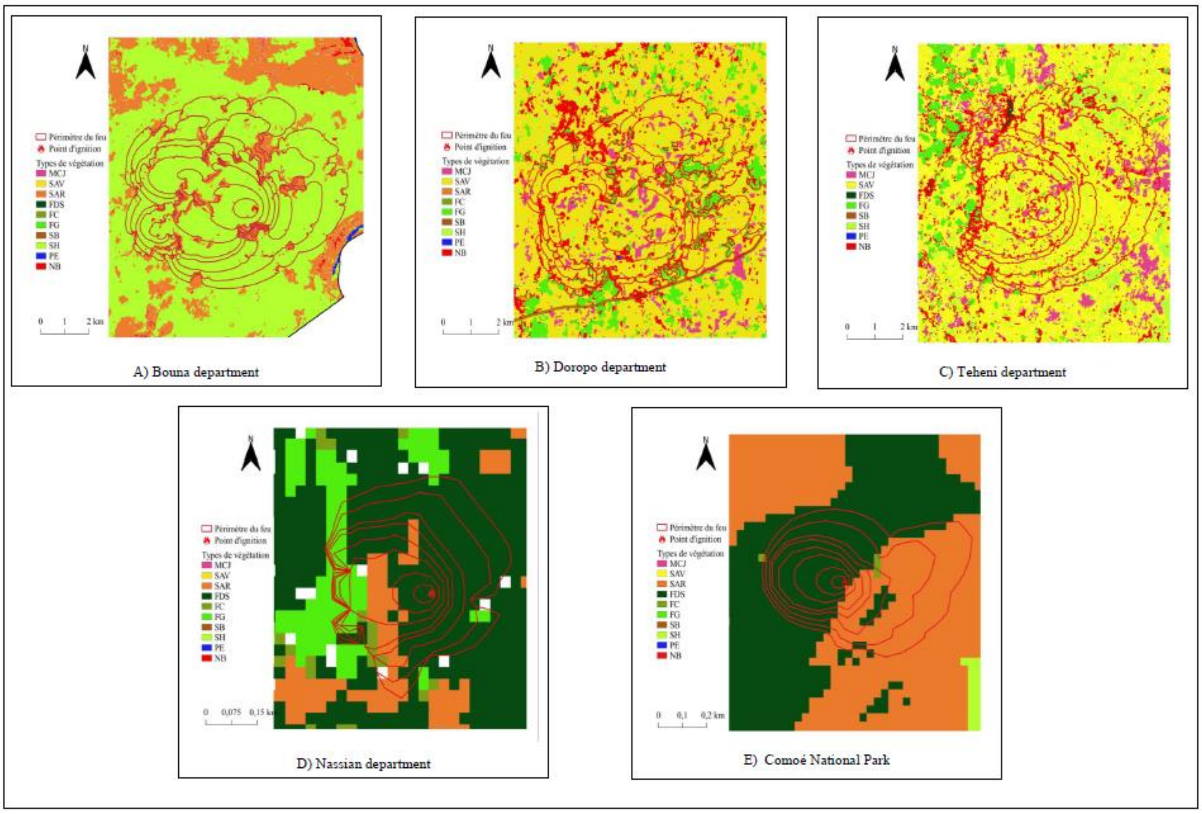
In addition to particulate and gas emissions, fire emits a large amount of heat that depends on several factors (fuel type and density, rate of spread, degree of combustion, etc.). Figure 9 shows the prediction of the amount of heat emitted per square meter. The results of this study indicate that in the department of Bouna, the heat released per unit area varies from 4554,01 to 29889,55 kJ.m^{-2}. Then, in Doropo department, the heat released per unit area varies from 642,29 to 40867,22 kJ.m^{-2}. Then, the heat released per unit area varies from 1352,16 to 40719,60 kJ.m^{-2} in Teheni department. Then again, the heat released per unit area varies from 635,88 to 7595,98 kJ.m^{-2} in Nassian department. Finally, in Comoé National Park, the heat released per unit area varies from 713,34 to 7555,18 kJ.m^{-2}.

In general, Doropo and Teheni departments have the highest heat of fire per unit area, with a value of 40867,22 and 40719,60 kJ.m^{-2} followed by Bouna department with a value of 29889,55 kJ.m^{-2}. On the other hand, Nassian department and Comoé National Park have the lowest heat output per unit area with a value of 7555, 18 and 7595,98 kJ.m^{-2} during 7 hours of simulation.

3.8. Spread direction

Figure 10 shows the direction of fire propagation during 7 hours of simulation time. The results revealed that in all five (05) study cases, the fire propagated in the presence of a light breeze from a northerly direction over the course of a few hours before moving to a northeasterly direction depending on the location of the fire ignition point.

For the same time intervals, the distances traveled in the five (05) study cases are very similar in all directions. With the effect of the wind, we can observe for the same time steps, large distances are traveled in the wind direction, and short distances on the opposite side of the wind. In addition, the propagation of fire is very fast at certain times in the presence of wind.



A) Bouna department

B) Doropo department

C) Teheni department

D) Nassian department

E) Comoé National Park

Figure 3: Fire perimeters based on fuel models for the five case studies

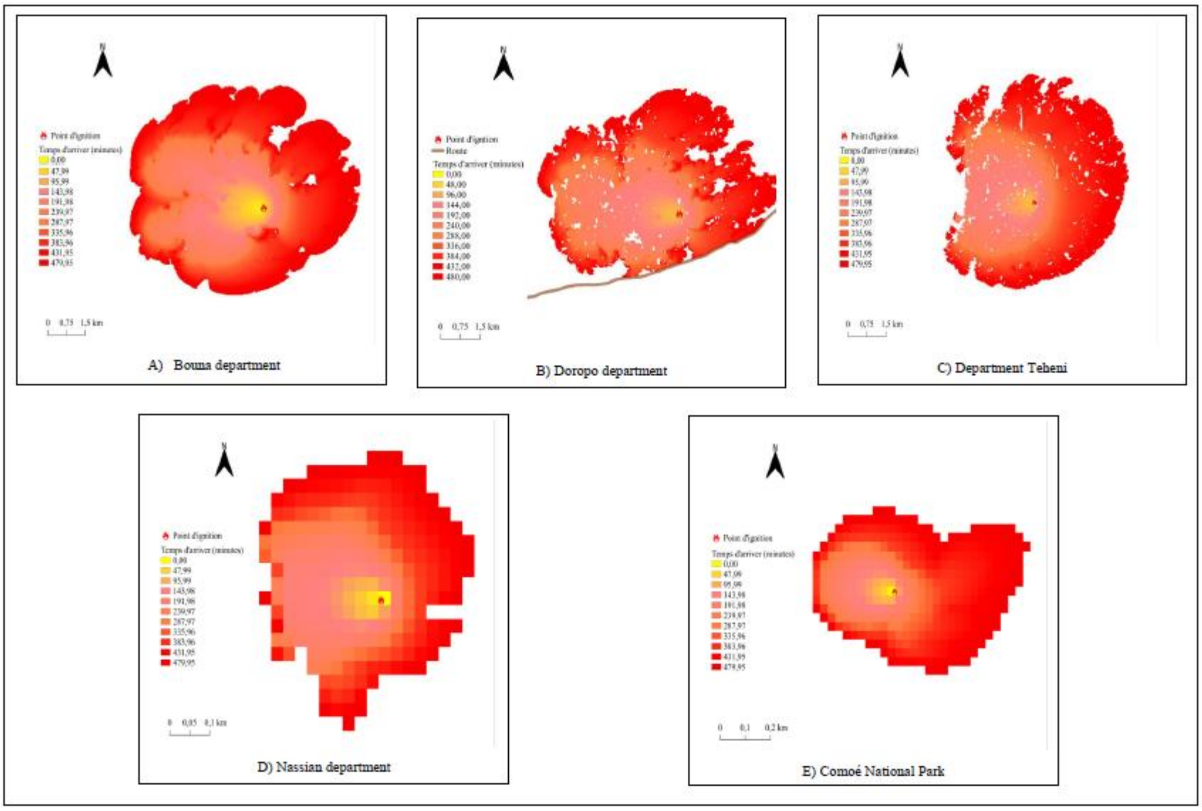

A) Bouna department
B) Doropo department
C) Department Teheni
D) Nassian department
E) Comoé National Park

Figure 4: Time of arrival of the five case studies during 7 hours of simulation

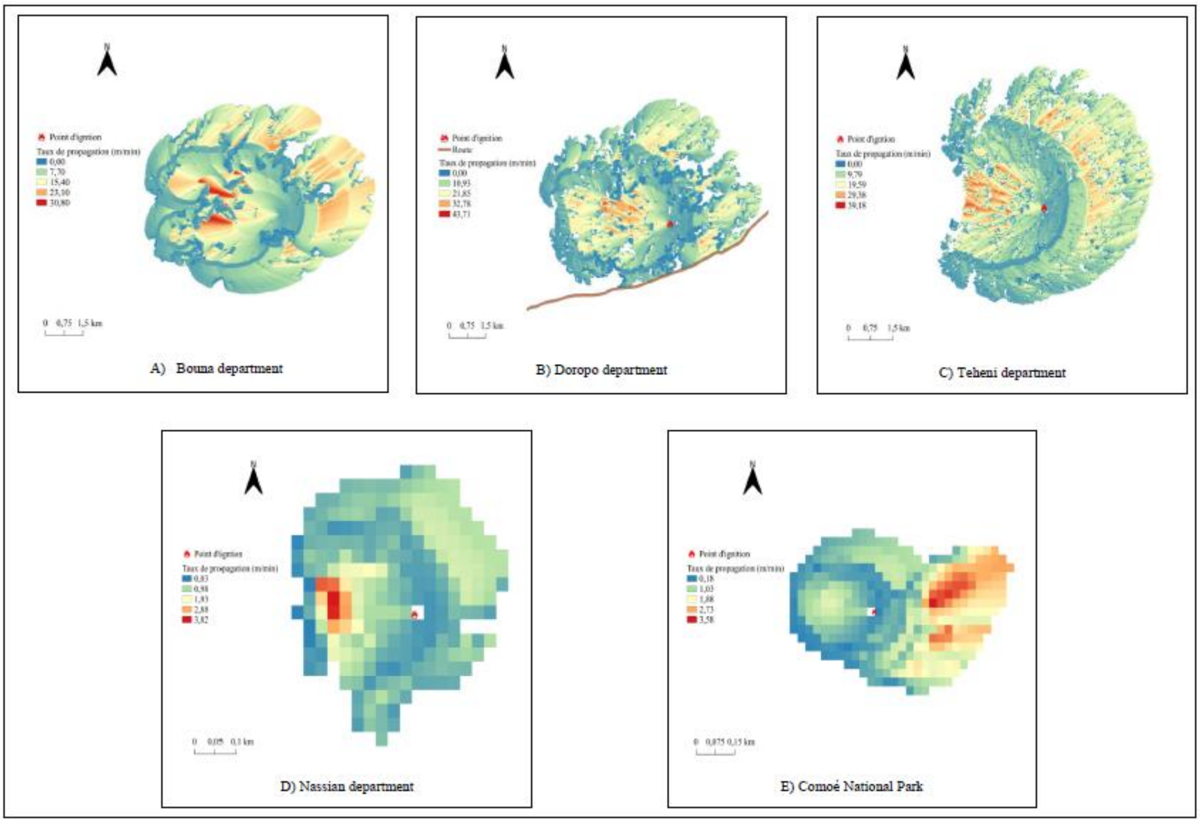
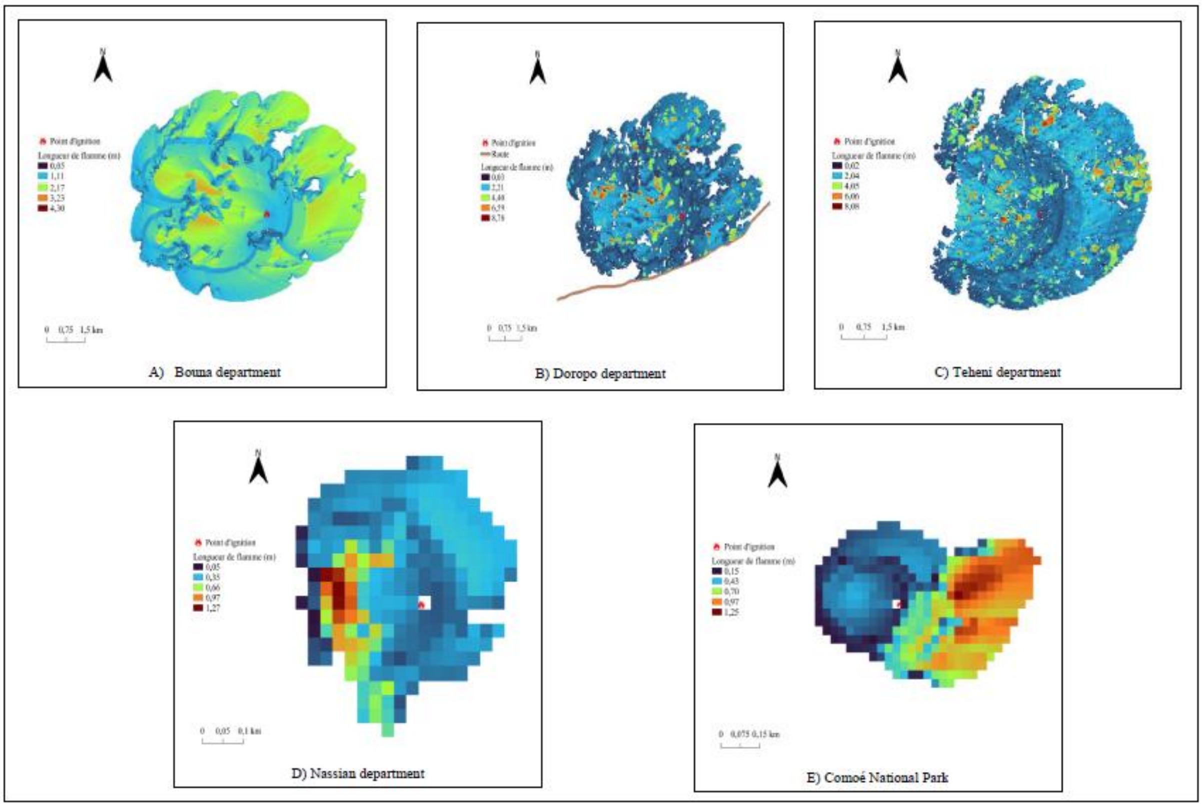

A) Bouna department
B) Doropo department
C) Teheni department
D) Nassian department
E) Comoé National Park

Figure 5: Propagation speed in the five study cases during 7 hours of simulation



A) Bouna department

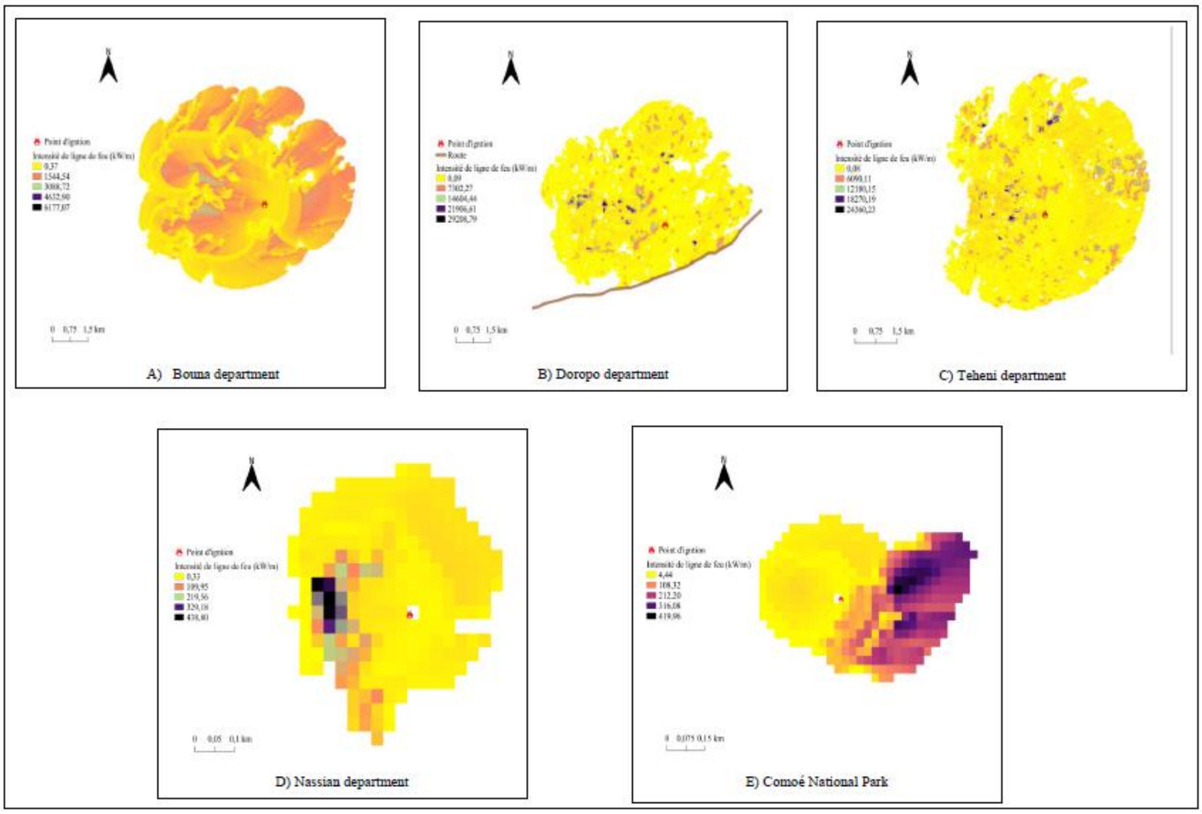
B) Doropo department

C) Teheni department

D) Nassian department

E) Comoé National Park

Figure 6 : Flame length in the five study cases during 7 hours of simulation



A) Bouna department

B) Doropo department

C) Teheni department

D) Nassian department

E) Comoé National Park

Figure 7: Fireline intensity in the five study cases during 7 hours of simulation

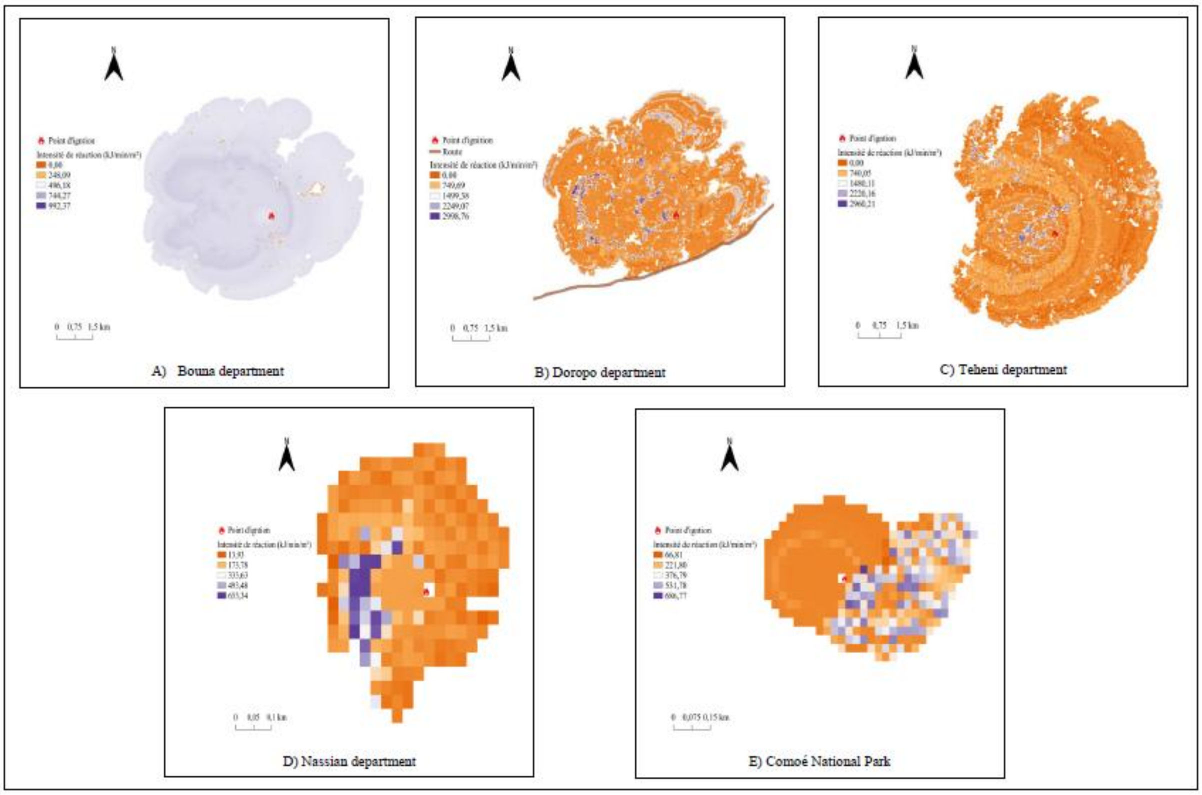


Figure 8: Reaction intensity in the five case studies during 7 hours of simulation

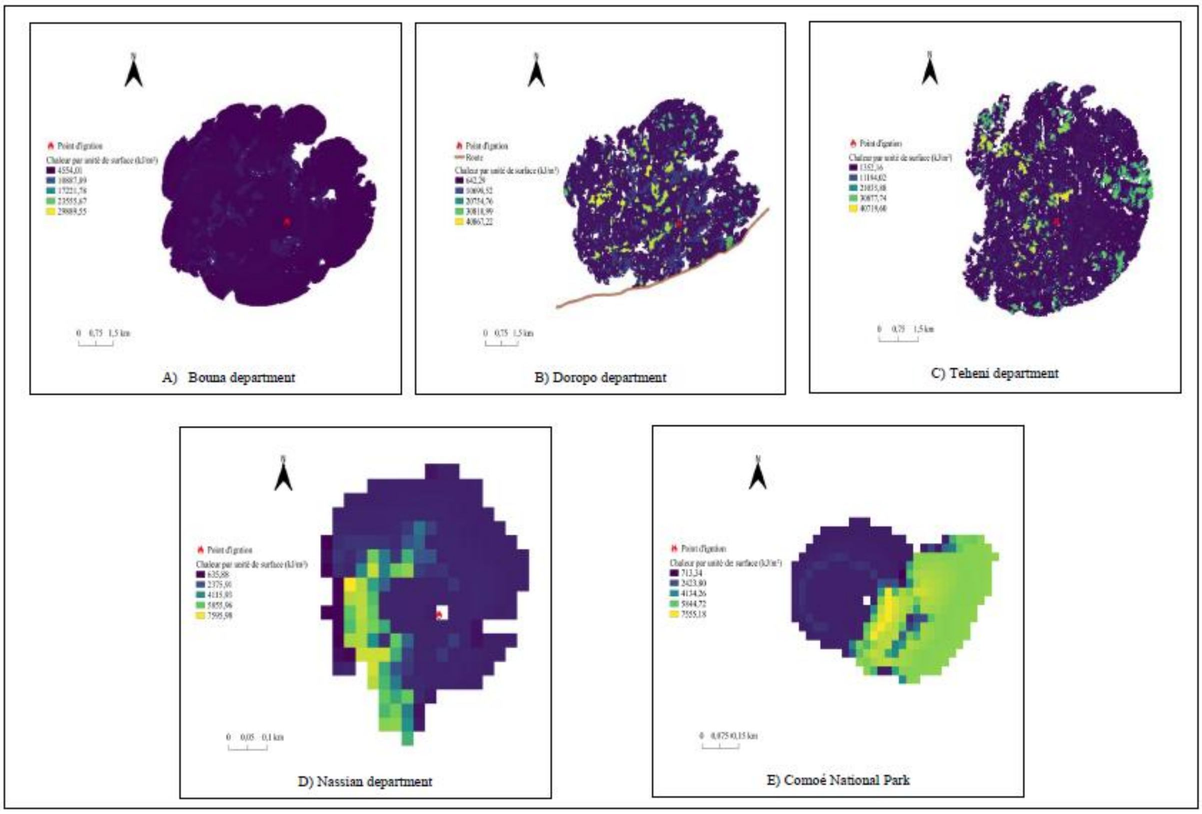
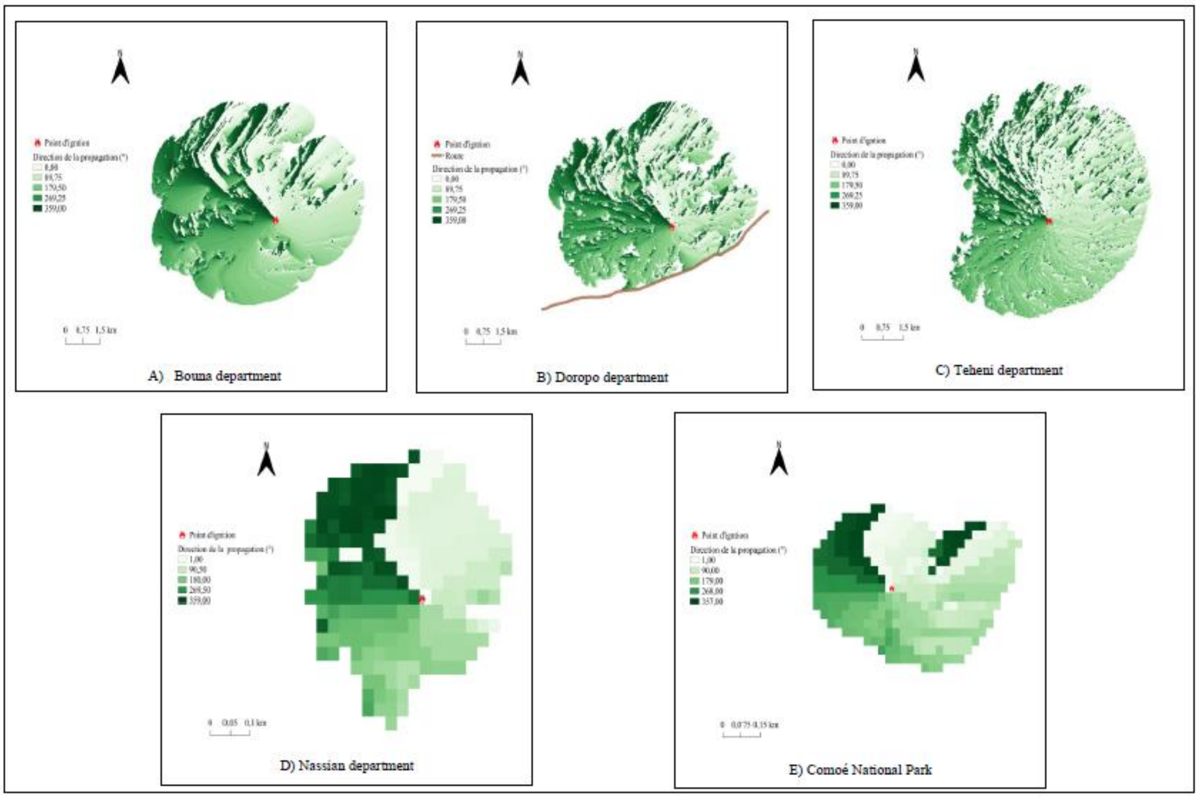


Figure 9: Heat per unit area in the five study cases during 7 hours of simulation



A) Bouna department
B) Doropo department
C) Teheni department
D) Nassian department
E) Comoé National Park

Figure 10 : Direction of fire spread in the five case studies

IV. Discussion

Currently, there are no studies conducted on the propagation and behavior of fire using fire simulator software in Côte d'Ivoire. Our study is the first attempt and therefore there will be no linking of results. FARSITE results indicated that, in general, the simulation study areas characterized by predominantly grass vegetation types, such as the grass savanna (HS), shrub savanna (SAV) and crop-fallow mosaic (CFM) fuel patterns have higher fuel characteristics, such as higher fuel biomass, higher flame source, higher fire intensities, faster rate of spread, larger amount of heat release and larger area covered by the fire. This can be explained by the fact that grasses are light fuels of fine vegetation and therefore less humid. There is also the moisture content of the fuel to consider, which is very important in determining the fire behavior. [34] confirm that the speed of the flame front depends on the moisture content and the calorific value of the vegetation. A high moisture content will slow down the fire because most of the thermal energy will be used to eliminate it in the fuels. Conversely, it is relatively low in tree formations with dense undergrowth, where the vegetation forms a screen against wind, heat radiation and horizontal convection. Living trees generally contain a lot of moisture, while dead trees contain very little, depending on the climate. The size and arrangement of fuels is also important: large fuels require more energy to ignite and burn than light fuels. The slope of the land has the same effect as wind [15,36]. In the same vein, [37] states that wind speed and direction are parameters that drastically affect fire propagation. This is true in our case. The wind more or less modified the direction and acceleration of the fire front on the five (05) study cases of the simulation. The intensity of the reaction generally depends on the temporary supply of oxygen by the air layers. This supply is often favored by the effects of wind, which explains the very contrasted aspect of the propagation pattern under the effect of wind. On the other hand, the intensity of the reaction also depends on the type of fuel and the impulse of the fire. This is justified by [15,36]. which states that the wind speed and direction are parameters that drastically affect the propagation of fire. In this study, the Doropo area had a road indicated as a barrier in FARSITE. Water and bare ground are natural barriers that limit fire spread. The above output variables are good indicators for predicting possible provisions for safety and property protection. Potential uses of these files include planning, operational tactics, and anticipating trigger points. The FARSITE simulation therefore allows for the prediction of fire behavior for the purpose of planning prevention or suppression strategies.

Although the case studies analyzed were characterized by a complex range of fuels, topography, and meteorological factors under which fires burned, the values of fire spread rate and intensity obtained from FARSITE simulations for predominantly herbaceous and forested fuel types are similar to those reported in previous empirical studies conducted in savanna ecosystems [15,16,17,38,39,40,41]. In contrast, shrub and forest vegetation types showed lower mean values of spread rate as well as flame length and fire intensity.

V. Conclusion

The main objective of this study, i.e., modeling the propagation and behavior of bushfires in the Bounkani region, was achieved. This was achieved by using satellite remote sensing data (LANDSAT and SRTM) with meteorological data (wind, temperature, precipitation, humidity) freely available on the internet. GIS software, the main tool of this study, was used to process and organize these data before integrating them into FARSITE for simulation.

Among the 5 case studies, the results reveal that the departments of Doropo and Teheni which have similar fuel patterns characterized by savanna tree (SAR), savanna shrub (SAV) and mosaic crop-fallow (MCJ) have the highest values of fire behavior characteristics (fire speed, length, intensity, amount of heat and direction). As for the area burned by the simulated fire, the Bouna department recorded the highest value. Indeed, these characteristics of fire behavior, notably the speed of propagation varies between 0.00 to 43.71 $m.min^{-1}$ with a length of 0.03 to 8.78 m and the heat released during combustion was between 642.29 and 40867.22 $kJ.m^{-2}$, with a high intensity ranging from 0.09 to 29208.79 $kW.m^{-1}$ and also a power released by the fire varying between 0.00 to 2998.76 $kJ.min^{-1}$ m^{-2}. Conversely, the results show that Nassian County and CNP presented the lowest values of the output variables after the simulation with FARSITE software. These areas are characterized by predominantly woody fuel patterns (gallery forests, dense forests, wooded savannahs) resulting in slower spread rates ranging from 0.03 to 3.82 m min^{-1}, a short flame length ranging between 0.05 and 1.27 m and with a less intense fire from 0.33 to 438.80 $kW.m^{-1}$ then the power released during the fire ranged from 13, 93 to 686, 77 $kJ.min^{-1}$ m^{-2} including a quantity of heat between 635.88 and 7595.98 $kJ.m^{-2}$ for all the outputs analyzed. In general, it can be noticed that the contour of the fire does not have the same shapes and also the increase of the burned area was not constant, because the local characteristics (topography, fuel, climate) determine a more or less important advance of the fire. Apart from the wind (speed and direction) which had a significant influence on the output variables, the low slope of our study area depending on the ignition point had more or less effect on these variables. In addition, the simulation showed that the fire stops or goes out when it encounters an obstacle or a barrier, thus, does not seem to favor the propagation of the fire.

In spite of some complexity encountered in this study, the results are that even in agreement with the ordinary observations, which prove the effectiveness and performance of FARSITE in the study of the dynamics and behavior of fire. Despite these results, the study could be limited by the quality of the data provided to make the simulation. However, they do provide a perspective for understanding the risk of bushfire in this savannah area.

References

[1]. Shekede, M D. ; Gwitira, I. & Mamvura, C. (2019): Spatial modelling of wildfire hotspots and their key drivers across districts of Zimbabwe, Southern Africa, Geocarto International, DOI: 10.1080/10106049.2019.1629642

[2]. FAO. (2009). Feux de forêts : Les pays en développement plus vulnérables. http://www.un.org/apps/newsFr/storyF.asp?NewsID=19702&Cr=incendies&Cr1=FAO#.VFEAMhY0-qk

[3]. Soro, B. ; Sokouri, D. P. ; Dayo, G. K. ; N'guetta, A. S. P. & Yapignaoré, C. V. (2015). Caractérisation des bovins de race Baoulé dans le "Pays Lobi" de Côte d'Ivoire : rôles socioéconomiques, modes d'élevage et contraintes de production. Tropicultura, 33 (2), pp. 111-124

[4]. Vieira, D. C. S. ; Fernández, C. Vega, J. A. & Keizer, J. J. (2015). Does soil burn severity affect the post-fire runoff and interrill erosion response? A review based on metaanalysis of field rainfall simulation data. Journal of Hydrology, 523(15): 452–464. DOI: 10.1016/j.jhydrol.2015.01.071

[5]. Stoof, C. R. ; Ferreira, A. J. D. ; Mol, W. ; Van den Berg, J. ; De Kort, A. ; Drooger, S. ; Slingerland, E. C. ; Erik, C. ; Mansholt, A. ; Ayolt, U. ; Ferreira, C. S. S. ; Carla, S. S. & Ritsema, C. J. (2015). Soil surface changes increase runoff and erosion risk after a low-moderate severity fire. Geoderma, 239 (240), pp. 58-67 DOI: 10.1016/j.geoderma.2014.09.020

[6]. BNETD., ETC TERRA. & RONGEAD., (2016). Analyse qualitative des facteurs de déforestation et de dégradation des forêts en Côte d'Ivoire ; Ministère de l'Environnement et du Développement Durable : Abidjan, Côte d'Ivoire, 114p

[7]. CNDFB. (2018). Dégâts des feux de brousse en Côte d'Ivoire entre 1983 et 2004. Comité National de Défense de la Forêt et de lutte contre les feux de Brousse (CNDFB), Abidjan, 1 p.

[8]. Kouassi, K. J-L., (2019). Variabilité climatique, dynamique des feux de végétation et perceptions locales dans le bassin versant du N'Zi (centre de la Côte d'Ivoire). Thèse de doctorale, INPHB, Yamoussoukro, Côte d'Ivoire, 250p

[9]. Kambire, S. ; Coulibaly,T. J. H. ; Coulibaly,N. ; Savane, I. ; Gone, L.D. ; Kouadio, K. C. A. ; Coulibaly, H. S. J. P. ; Cissé, S. ; Camara, I. & Sylla, G. (2021). Contribution of satellite imagery to the characterization of the relationship between climate and pyrological variables of bush fires in the savannah one (case of the Bounkani region). Environment & Ecosystem Science, 5 (1), pp. 64-72.

[10]. Finney, M. (2004). FARSITE : fire area simulator model development and evaluation. Res. Pap. RMRS-RP-4, Ogden, U T : U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

[11]. Andrews, P. L. (2008). BehavePlus: fire modeling system (user's guide). 4 ed. Ogden: USDA Forest Service, Rocky Mountain Research Station. 123 p.

[12]. Prince, D., Shen, C. & Fletcher, T. (2017). Modèle semi-empirique pour la propagation du feu dans les arbustes avec des éléments combustibles et des flammes spatialement définis. Fire Technol 53, 1439–1469. https://doi.org/10.1007/s10694-016-0644-9

[13]. Mistry, J. & Berardi, A. (2005). Assessing Fire Potential in a Brazilian Savanna Nature Reserve. Biotropica, 37 (3), pp. 439-451.

[14]. Nader, B. & Milad, H. (2015). Evaluation des simulations de feux de forêts. Modélisation et simulation. Université Pascal Paoli, France. NNT : 2015CORT0005. tel-01403922

[15]. Millimono, T. N. ; Badiane, D. ; Diakhate, M. ; Bah, A. ; Sall, S. M. ; Toure, I. & Diaby, I (2019). Bushfires spread modelling over Malea in Northeastern Guinea. African Journal of Environmental Science and Technology, 13 (4), pp. 135-148. DOI: 10.5897/AJEST2019.2652

[16]. Berjak, S. G. & Hearne, J. W. (2002). An improved cellular automaton model for simulating fire in spatially heterogeneous Savanna system. Ecological Modeling, 148, pp. 133-151.

[17]. Mbow, C. ; Goïta, K. ; & Benie, G. (2004). Spectral indices and fire behavior simulation for fire risk assessment in savanna ecosystems. Remote Sensing of Environment, 91 (1), pp. 1-13. 10.1016/j.rse.2003.10.019.

[18]. Sangne, C. Y. ; Bamba, I. ; Kpangui, B. K. ; Kouakou, A. K. & Bari, Y. S. S. (2019). Emprise des champs d'anacarde sur les forêts et savanes en milieu paysan autour du parc national de Comoé. International Journal of Biological and Chemical Science, 13 (2), pp. 662-675. http://www.ifgdg.org

[19]. Mbow, C. (2000). Caractéristiques spatio-temporelles des feux de brousse et leur relation avec la végétation dans le Parc National du Niokolo Koba (Sud-est du Sénégal). Thèse de Doctorat de Troisième Cycle en Sciences de l'Environnement. ISE, Faculté des Sciences et Techniques, UCAD, Sénégal, 120 p.

[20]. Kambiré, B. (2010). L'agriculture vivrière du Nord-est de la Côte d'Ivoire en « régression » : un danger pour les centres urbains ivoiriens, 14 p.

[21]. Guillaumet, J. L. & Adjanohoun, E. (1971). La végétation de la Côte d'Ivoire In : le milieu naturel de la côte d'ivoire, 262 p.

[22]. N'Doume, C. (2018). Production cartographique dans le cadre de la surveillance spatiale des terres (SST) en Côte d'Ivoire, BNEDT, CIGN, Abidjan, Cote d'Ivoire. 27 p.

[23]. OIPR. (2019). Occupation du sol du Parc national de la Comoé et sa zone périphérique en 2017. Rapport de Direction de Zone Nord-Est, Service Suivi Ecologique et Système d'Information Géographique. 15 p.

[24]. Finney, M. A. ; Brittain, S. ; Seli, R. C. ; McHugh, C.W. & Gangi, L. (2019). FlamMap:Fire Mapping and Analysis System . Available from https://www.firelab.org/document/flammap-software

[25]. Rothermel, R.C. (1972). A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Research Paper INT-115, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station : Ogden, UT, USA, 40 p.

[26]. Anderson, H. E. (1982). Aids to determining fuel models for estimating fire behavior. General Technical Report INT-122. Ogden, UT : U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 28 p.

[27]. Frandsen, W. H. (1971). Fire Spread through Porous Fuels from the Conservation of Energy. Combustion and Flame, 16, pp. 9-16.

[28]. Moretti, (2015). Modélisation du comportement des feux de forêt pour des outils d'aide à la décision. Modélisation et simulation. Thèse de Doctorat, Université Pascal Paoli, France, 189 p.

[29]. Keane, R. E. ; Burgan, R. & Van Wagtendonk, J. (2001). Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. International Journal of Wildland Fire, 10, 301.

[30]. Scott, J. H. & Burgan, R. E. (2005). Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 80 p.

[31]. Kanga, S. ; Sharma, L. ; Pandey, P. C. ; Nathawat, M. S. (2014). GIS modeling approach for forest fire risk assessment and management. International Journal of Advancement in Remote Sensing, GIS and Geography,2 (1), pp. 30-44

[32]. Leprun, J. C. & Olivier Da Silveira, C. (1992). Analogies et particularités des sols et des eaux de deux régions semi-arides : le Sahel de l'Afrique de l'Ouest et le Nordeste brésilien, pp. 131-152.

[33]. Leprun, J. C. (1997). Comparative Ecology of Two Semi-Arid Regions: the Brazilian Sertao and the African Sahel. In H. Paquet et al., Soils and Sediments. Springer-Verlag Berlin Heidelberg. Chapter 8, 157-158.

[34]. FAO. (2010). Global Forest Resources Assessment. Main Report, 75 p. http://www.fao. org/docrep/013/i1757f/i1757f00.htm

[35]. Dickinson, K. J. M. & Kirkpatrick, J. B. (1985). The flammability and energy content of some important plant species and fuel componentsn in the forests of southeastern tasmania. 12 : 121-134.

[36]. Sanjuan, G. ; Brun,C. ; Margalef1, T. & Cortes, A. (2014).Wind field uncertainty in forest fire propagation prediction. Procedia Computer Science, 29, pp. 1535-1545.

[37]. Khalil, A. & Saad, A. (2012) Simulation numérique du comportement des feux de forêt par le logiciel Farsite. Thèse de Doctorat, Université Libanaise. Liban. 89p.

[38]. Brou, A. D. V. (2013). Un modèle hybride stochastique déterministe de propagation des feux de savane. Thèse de Doctorat, Université Félix Houphouët Boigny, Abidjan, Côte d'Ivoire, 115 p.

[39]. N'Dri, A. B. ; Soro, T. D. ; Gignoux, J. ; Dosso, K. ; Koné, M. ; N'Dri, J. K. ; Koné, N. A. & Barot, S., (2018a). Season affects fire behavior in annually burned humid savanna of West Africa. Fire Ecology. 14 (2), 5. doi: 10.1186/s42408-018-0005-9

[40]. N'Dri A. B., Fongbe M., Soro T. D., Gignoux J., Kone M., Dosso, K., N'dri, J. K., Kone, N. A. & Barot S., (2018b). Principaux indices de l'intensité du feu dans une savane Guinéenne d'Afrique de l'Ouest. International Journal of Biological and Chemical Sciences. 12 (1), 266. doi: 10.4314/ijbcs.v12i1.21.

[41]. Afelu, B. & Kokou, K. (2015). Paramètres physiques d'évaluation du comportement des feux de végétation au Togo. International Journal of Biological and Chemical Sciences. 9 (4), pp. 2091-2105. DOI: http://dx.doi.org/10.4314/ijbcs.v9i4.31