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Numerical Investigation of Crude Oil Spilled Mangrove Vegetation: A Fire Risk Assessment Modeling of Uvwie Local Government Area of Delta State, Nigeria

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ABSTRACT

Numerical risk assessment of an investigative study on small single-lit fire in a simulated environment is carried out. Crude oil from Ubege oil field, Delta state, Nigeria was spilled onto a set of logs of wood, representing the mangrove vegetation. The risk assessment resultant from this study showed that should there be a fire incident, the havoc to be wrecked on the adjoining communities and the immediate community could be devastating. The simulations were carried out by keeping Elapse time and length-to-width ratio constant at 3 hours and 2.3, respectively. The numerical risk modeling showed that over 200, 000 lives and over 150,000 houses, wildlife, and even aquatic lives and billions of dollars of properties could be destroyed by fire. The numerical risk assessment quantified showed that the following communities could be at risk, should there be a crude spill and a source of ignition: the Federal University of Petroleum Resources, Effurun, Iteregbe, Ogbomro, Okorikpereh, parts of Okuokoko, parts of Agbarho. From the study, and its simulations and investigative study, it is strongly recommended that a fire station is established in this vicinity to mitigate a possible fire outbreak.

Keywords: *Numerical fire risk assessment, Crude oil spill, Modelling.*

1.0 INTRODUCTION

The question of how far a fire, charged with crude oil, could travel has been a challenge in Nigeria's Delta. Worst still, the threat of the devastating effect such fires may cause as it travels remains a challenging field of combustion in the African continent. The oil spill which resulted in countless destruction of lives, property and the environment almost two decades ago, in Jesse, Ethiope LGA, Delta State, Nigeria is still fresh in the minds of the people. It was reported that the fire lasted for more than two weeks. The fire, in its fury, never left any object in its way; rather, it destroyed and converted all such obstructions to ashes including man, beast, houses, farmlands, properties and the like. The death toll was estimated to be 1,082 [1]; properties, destroyed, were countless.

The object of this work is to carryout a numerical risk assessment of the fire resulting from the crude oil spill. Indeed, the science of modeling bushfire is the art of moving from fire qualification to fire quantification. By using the fuel model as key input to fire models, wildfire modeling attempts to reproduce fire behavior, such as how quickly the fire spreads, in which direction, how much heat it generates, whether the fire transitions from the surface (a "surface fire") to the tree crowns (a "crown fire"), as well as extreme fire behavior including rapid rates of spread, fire whirls, and tall well-developed convection columns. Fire modeling also attempts to estimate fire effects, such as the ecological and hydrological effects of the fire, fuel consumption, tree mortality, and amount and rate of smoke produced [2].

An average of 240,000 barrels of crude oil are spilled in the Niger delta every year, mainly due to unknown causes (31.85%), third party activity (20.74%), and mechanical failure (17.04%) [3].For a total of 5576 spills 5235 were detected [5]; the area covered by this research is the Niger Delta region covering Edo, Delta, Ondo, Rivers, Bayelsa, Abia, Imo, Akwa Ibom, Cross-River States.

There is dearth of literature dealing with the issues of conflagration in situ and theirpossible impact on the ecological equilibrium [4], the present work is concerned with numerical simulation of wild land fires in order to understand and predict fire behavior [2]. The aftermath of this study is to ultimately aid wild land fire suppression, namely increase safety of firefighters and the public, reduce risk, and minimize damage, aid in protecting ecosystems, watersheds, and air quality [2].

1.2. Mathematical Modeling

The Behave Plus fire modeling system is based on a collection of models that describe fire behavior, fire effects, and the fire environment. Behave Plus is the successor to the BEHAVE fire behavior prediction and fuel modeling system [9] to [12]. It is called the Behave Plus fire modeling system to reflect its expanded scope [6].

Fire spread, R:

For direction of maximum spread or for any specified direction, Rate of spread, intensity, and flame length of surface fire was modeled using [7]:

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \qquad [1]$$

where

$$I_R = \Gamma' w_n h n_M n_S \qquad [2]$$

$$\Gamma' = \Gamma'_{max} \left(\frac{\beta}{\beta_{op}}\right) A_{exp} \left[A\left(1 - \frac{\beta}{\beta_{op}}\right)\right] \qquad [3]$$

$$\Gamma'_{max} = \sigma^{1.5}(495 + 0.059\sigma^{1.5})^{-1} \qquad [4]$$

$$\beta_{op} = 3.348\sigma^{-0.8189} \qquad [5]$$

$$A = \frac{1}{(4.774\sigma^{-1} - 7.27)} \qquad [6]$$

$$\eta_M = 1 - 2.59\frac{M_f}{M_x} + 5.11\left(\frac{M_f}{M_x}\right)^2 - 3.52\left(\frac{M_f}{M_x}\right)^3 \qquad [7]$$

$$\eta_s = 0.174 Se^{-0.19} \qquad [8]$$

$$\xi = (192 + 0.2595\sigma)^{-1} exp[(0.792 + 0.681\sigma^{0.5})(\beta + 0.1)] \qquad [9]$$

$$\phi_w = CU^B \left(\frac{\beta}{\beta_{op}}\right)^{-E} \qquad [10]$$

$$C = 7.47 \exp(-0.133\sigma^{0.55}) \qquad [11]$$

$$B = 0.02526\sigma^{0.54} \qquad [12]$$

$$E = 0.715 \exp(-3.59\, X\, 10^{-4} d) \qquad [13]$$

$$W_n = \frac{w_0}{1 + S_T} \qquad [14]$$

$$\phi_s = 5.275\beta^{-0.3}(tan\phi)^2 \qquad [15]$$

$$\rho_b = \frac{w_0}{\delta} \qquad [16]$$

$$\epsilon = exp(-138/\sigma) \qquad [17]$$

$$Q_{ig} = 250 + 1{,}116 M_f \qquad [18]$$

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$$\beta = \frac{\rho_b}{\rho_p} \qquad [19]$$

w_0, ovendry fuel loading $[lb./ft.^2]$, δ, fuel depth [ft], σ, fuel particle surface-area-to-volume ratio, [1/ft], M_f, fuel particle moisture content, $[\frac{lb.moisture}{lb.ovendry\ wood}]$, S_T, fuel particle total mineral content, $\left[\frac{lb.minerals}{lb.ovendry\ wood}\right]$, S_e, fuel particle effective mineral content, $\left[\frac{lb.silica-free\ mineral}{lb.ovendry\ wood}\right]$, U, wind velocity at midflame height, $[ft./min]$, $tan\ \phi$, slope, vertical rise/horizontal distance, M_f, moisture content of extinction [0.30], Q_{ig}, heat of preignition $\left[\frac{B.t.u.}{lb.}\right]$, β, packing ratio, ϵ, effective heating number, ρ_b, ovendry bulk density, $[lb./ft.^3]$, w_n, net fuel loading $[lb./ft^2]$, ϕ_w, wind coefficient, ξ, propagating flux ratio, η_s, mineral damping coefficient, η_M, moisture damping coefficient, β_{op}, optimum packing ratio, Γ', optimum reaction velocity $[min.^{-1}]$, Γ'_{max}maximum reaction velocity $[min.^{-1}]$, I_R reaction intensity $[B.t.u./ft.^2\ min.]$, R rate of spread $[ft./min.]$.

Rate of fire spread

The rate of fire spread was modeled by using [13].

Fire Intensity

The fire line intensity (I_B) at the centre of the fire front can be evaluated thus

$$I_B = m\ X\ \Delta H\ X\ ROS \qquad [20]$$

Where $m = \alpha\rho\delta$ is the fuel load = 0.7 [kJ/kg] [16]; ΔH is the heat yield of fuel = 18000 [kJ/kg] [14].

$$HRR = \dot{m}\ X\ \Delta H \qquad [21]$$

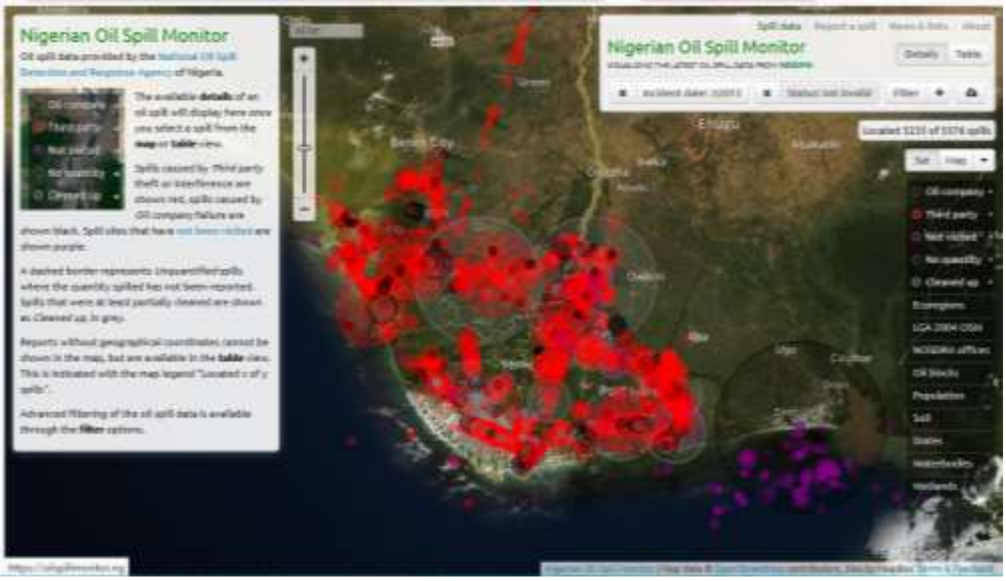

Figure 1: Oil spill monitor [5]

2.0 MATERIALS AND METHODOLOGY

2.1 Study Area

The study area is located in Uvwie Local Government Area of Delta State. Coordinates $5^0$31'N 5045'E/5.517^{0}N 5.750^{0}E. The region experiences moderate rainfall and moderate humidity for most part of the year. The climate is equatorial and is marked by two distinct seasons: the dry season and the rainy season. The dry season lasts from about November to April and is significantly marked by the cool "harmarttan" dusty haze from the north-east winds. The rainy season spans May to October with a brief dry spell in August, but it frequently rains even in the dry season. The area is characterized by tropical equatorial climate with mean annual temperature of 32.8 °C and annual rainfall amount of 2673.8 mm. There are high temperatures of 36 °C and 37 °C. The natural vegetation is of rainforest with swamp forest in some areas. The forest is rich in timber trees, palm trees, as well as fruit trees.

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Figure 2: Map of Uvwie LGA, Delta State, Nigeria[8].

2.2 Materials:

Crude oil from Ubeje Oilfield
Logs of wood
Stop watch

2.3 Methodology:

The object of this work is to carry out a numerical risk assessment of the fire resulting from the crude oil spill. Indeed, the science of modeling bushfire is the art of moving from fire qualification to fire quantification. By using the fuel model as key input to fire models, wildfire modeling attempts to reproduce fire behavior, such as how quickly the fire spreads, in which direction, how much heat it generates, whether the fire transitions from the surface (a "surface fire") to the tree crowns (a "crown fire"), as well as extreme fire behavior including rapid rates of spread, fire whirls, and tall well-developed convection columns. Fire modeling also attempts to estimate fire effects, such as the ecological and hydrological effects of the fire, fuel consumption, tree mortality, and amount and rate of smoke produced [2]. The fire behavior and other properties were characterized using behave plus.

The BehavePlus fire modeling system is a program for personal computers that is a collection of mathematical models that describe fire and the fire environment. It is a flexible system that produces tables, graphs, and simple diagrams. It can be used for a multitude of fire management applications including projecting the behavior of an ongoing fire, planning prescribed fire, and training. BehavePlus is the successor to the BEHAVE fire behavior prediction and fuel modeling system. Primary modeling capabilities include surface fire spread and intensity, crown fire spread and intensity, safety zone size, size of point source fire, fire containment, spotting distance, crown scorch height, tree mortality, wind adjustment, and probability of ignition [13].

3.0 RESULTS AND DISCUSSION

3.1 Fire shape

As the fuel loading (figures 3 to 9) increases so does the fire shape increase in size. Consequently, for 0% fuel loading, the fire shape is the smallest. However, for 100% fuel loading, the fire loading had its maximum shape.

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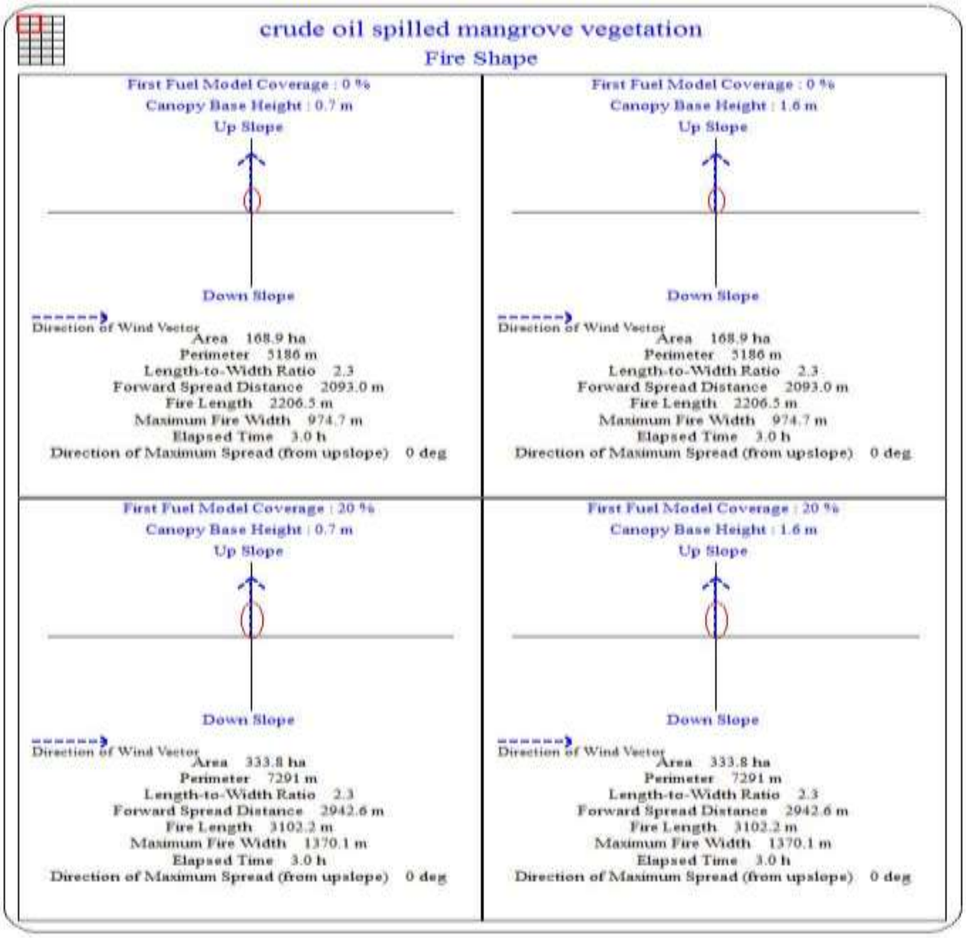

Figure 3: fire shape of combustion characterization from 0% to 20% fuel model loading at various canopy base heights

Figures 3 shows the fire shape at different fuel model change, canopy base height, wind vector direction, perimeter, length-to-width ratio, forward spread distance, fire length, max. fire width and elapsed time. It can be noticed that the higher the fuel model coverage, the faster and more spread the fire characteristics.

At 0% fuel loading, with a range of canopy base height of between 0.7 to 1.6 m, the Fire shape, depicted by the ring or oval shape, vertically, is less half the wind vector, with a combustion characterization as depicted in figure 3. The fire, at this fuel loading, is yet to be fully developed.

At 20% fuel loading, with a canopy base height of between 0.7 to 1.6 m, the fire shape, vertically, is half the wind vector, with combustion characterization as depicted in figure 3.

This trend, the rising or increase of the fire shape or size, increases with increase of the Fuel model coverage. However, the canopy base height does not affect the fire behavior.

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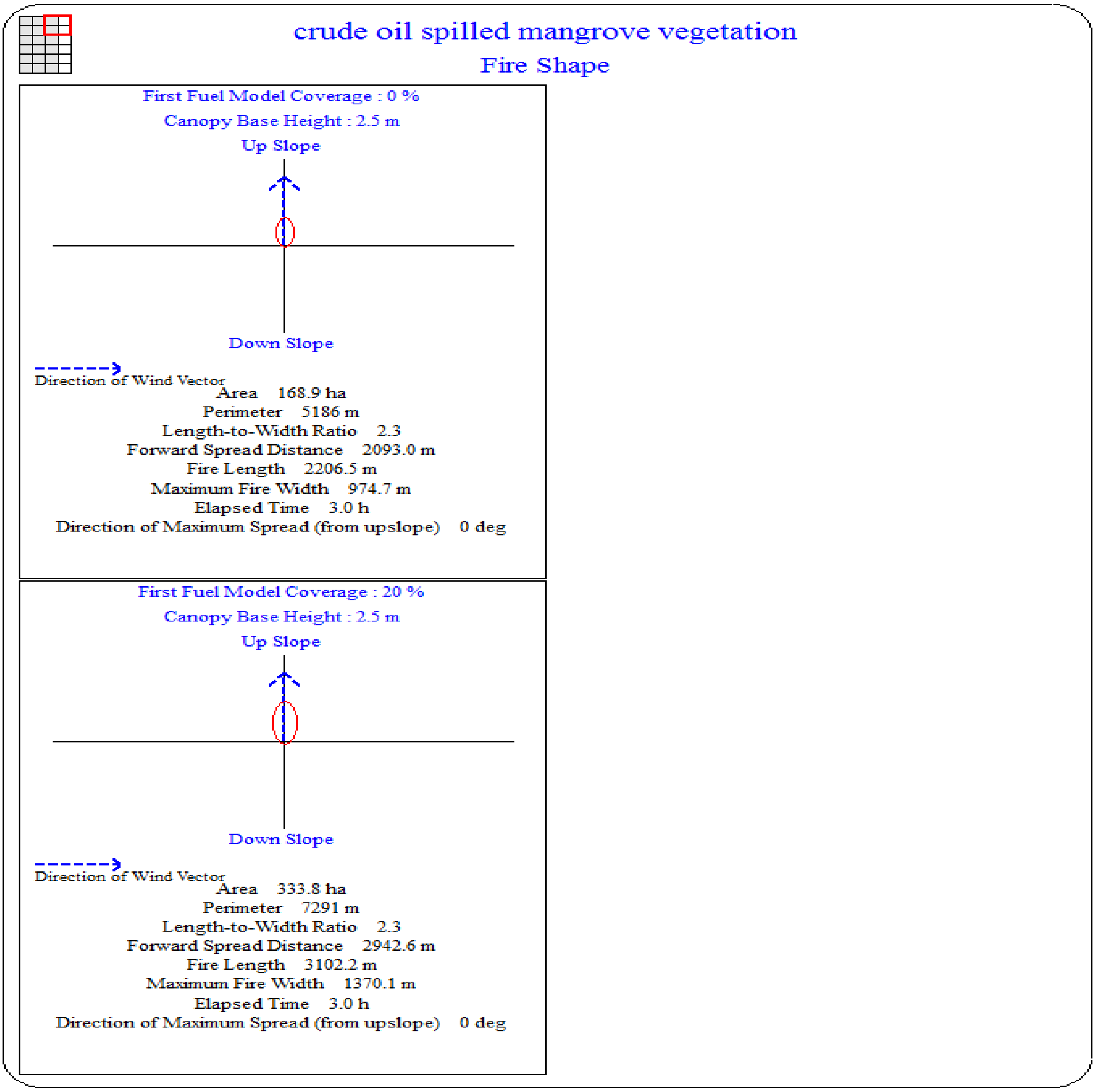

Figure 4: fire shape of combustion characterization from 0% to 20% at various canopy base heights continued.

Figures 4 shows the fire shape at different fuel model change, canopy base height, wind vector direction, perimeter, length-to-width ratio, forward spread distance, fire length, max. fire width and elapsed time. It can be noticed that the higher the fuel model coverage, the faster and more spread the fire characteristics.

At 0% fuel loading, with a range of canopy base height of 2.5 m, the Fire shape, depicted by the ring or oval shape, vertically, is less half the wind vector, with a combustion characterization as depicted in figure 4. The fire, at this fuel loading, is yet to be fully developed.

At 20% fuel loading, with a canopy base height of 2.5 m, the fire shape, vertically, is half the wind vector, with combustion characterization as depicted in figure 4.

This trend, the rising or increase of the fire shape or size, increases with increase of the Fuel model coverage. However, the canopy base height does not affect the fire behavior.

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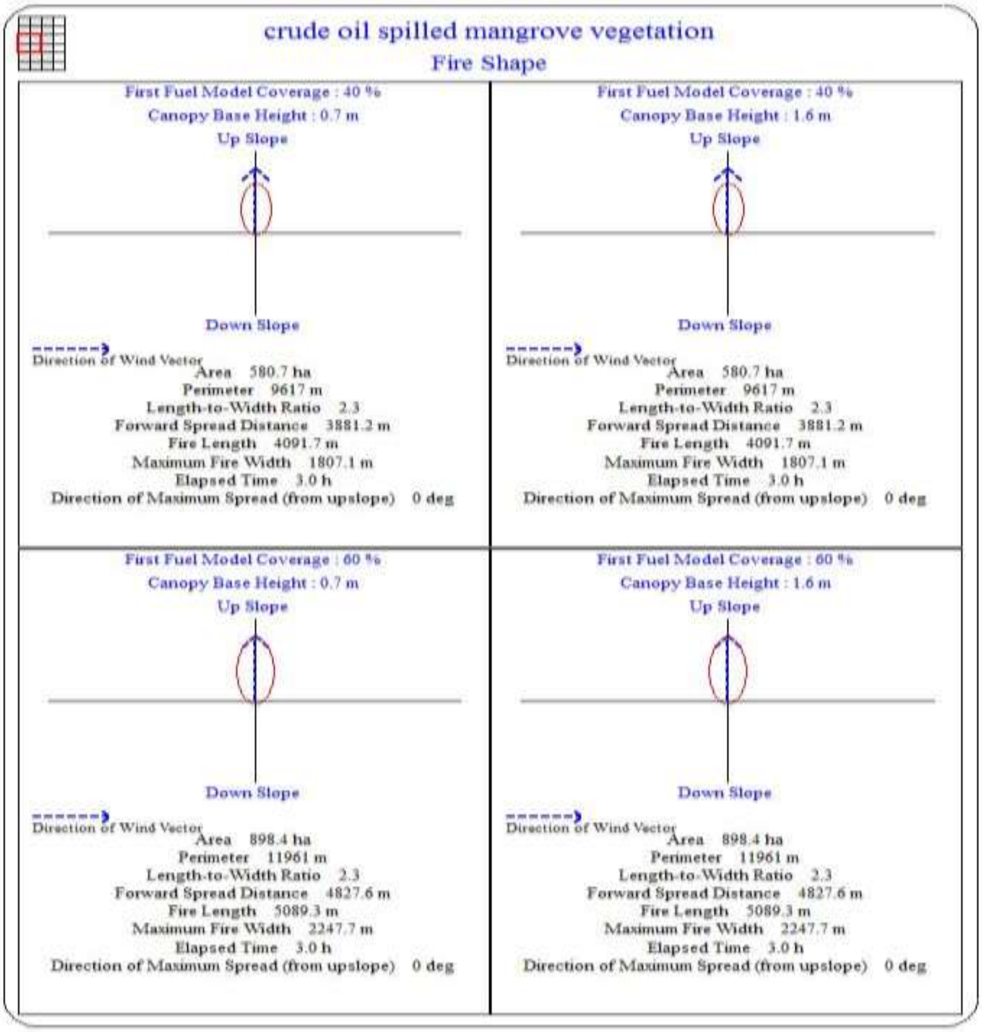

Figure 5: fire shape characterization of combustion from 40% to 60% of fuel loading at various Canopy Base Height.

Figures 5 shows the fire shape at different fuel model change, canopy base height, wind vector direction, perimeter, length-to-width ratio, forward spread distance, fire length, max. fire width and elapsed time. It can be noticed that the higher the fuel model coverage, the faster and more spread the fire characteristics.

At 40% fuel loading, with a range of canopy base height of between 0.7 to 1.6 m, the Fire shape, depicted by the ring or oval shape, vertically, is less half the wind vector, with a combustion characterization as depicted in figure 5. The fire, at this fuel loading, is yet to be fully developed.

At 60% fuel loading, with a canopy base height of between 0.7 to 1.6 m, the fire shape, vertically, is half the wind vector, with combustion characterization as depicted in figure 5.

This trend, the rising or increase of the fire shape or size, increases with increase of the Fuel model coverage. However, the canopy base height does not affect the fire behavior.

At 60% fuel model loading, the fire shape, from the positive x-axis or from the horizontal, is at the same height as the wind vector.

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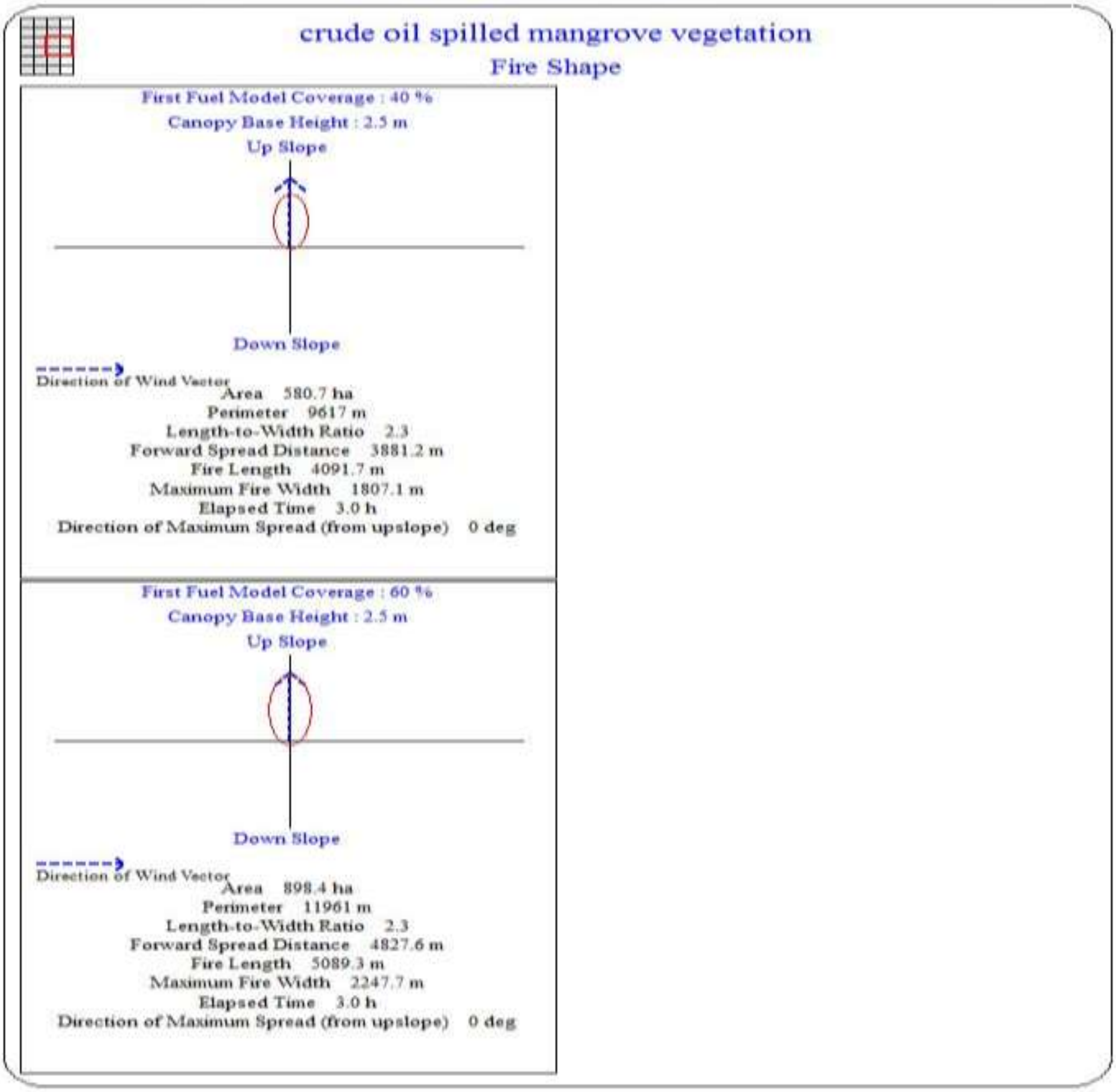

Figure 6: Fire shape characterization of combustion from 40% to 60% of fuel loading at various canopy base height.

Figures 6 shows the fire shape at different fuel model change, canopy base height, wind vector direction, perimeter, length-to-width ratio, forward spread distance, fire length, max. fire width and elapsed time. It can be noticed that the higher the fuel model coverage, the faster and more spread the fire characteristics.

At 80% fuel loading, with a range of canopy base height of between 0.7 to 1.6 m, the Fire shape, depicted by the ring or oval shape, vertically, is less half the wind vector, with a combustion characterization as depicted in figure 7. The fire, at this fuel loading, is yet to be fully developed.

At 100% fuel loading, with a canopy base height of between 0.7 to 1.6 m, the fire shape, vertically, is half the wind vector, with combustion characterization as depicted in figure 5.

This trend, the rising or increase of the fire shape or size, increases with increase of the Fuel model coverage. However, the canopy base height does not affect the fire behavior.

At 60% fuel model loading, the fire shape, from the positive x-axis or from the horizontal, is at the same height as the wind vector.

Interestingly, at 80 – 100% fuel model loading, the fire, as represented by the oval or ring shape, had enveloped the wind vector. The canopy base height does not, yet, affects the fire behavior.

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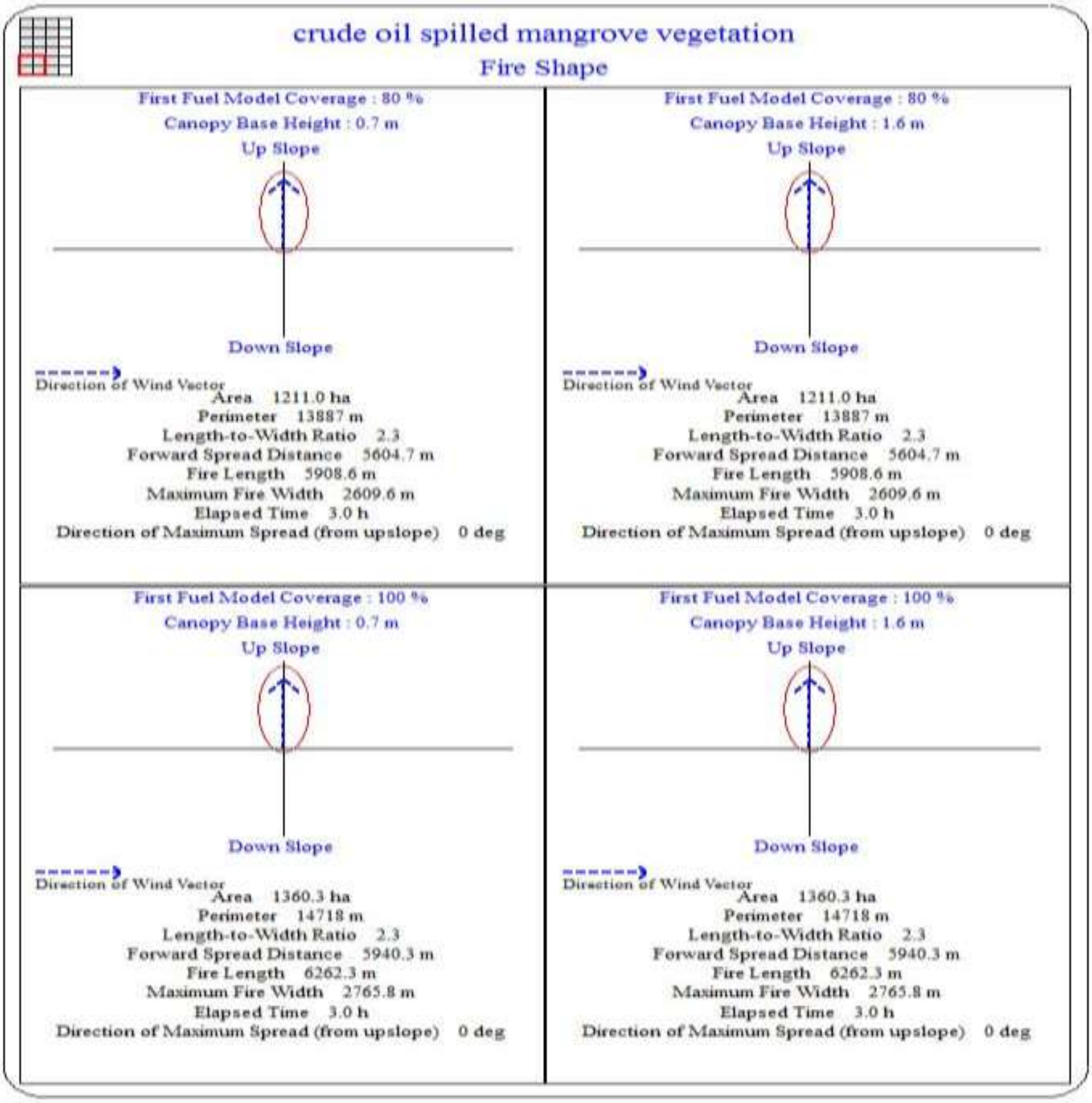

Figure 7: Fire shape characterization of combustion from 40% to 60% of fuel loading at various canopy base heights.

Figures 7 shows the fire shape at different fuel model change, canopy base height, wind vector direction, perimeter, length-to-width ratio, forward spread distance, fire length, max. fire width and elapsed time. It can be noticed that the higher the fuel model coverage, the faster and more spread the fire characteristics.

At 80% fuel loading, with a range of canopy base height of between 0.7 to 1.6 m, the Fire shape, depicted by the ring or oval shape, vertically, is less half the wind vector, with a combustion characterization as depicted in figure 7. The fire, at this fuel loading, is yet to be fully developed.

At 100% fuel loading, with a canopy base height of between 0.7 to 1.6 m, the fire shape, vertically, is half the wind vector, with combustion characterization as depicted in figure 8.

This trend, the rising or increase of the fire shape or size, increases with increase of the Fuel model coverage. However, the canopy base height does not affect the fire behavior.

At 60% fuel model loading, the fire shape, from the positive x-axis or from the horizontal, is at the same height as the wind vector.

Interestingly, at 80 – 100% fuel model loading, the fire, as represented by the oval or ring shape, had enveloped the wind vector. The canopy base height does not, yet, affect the fire behavior.

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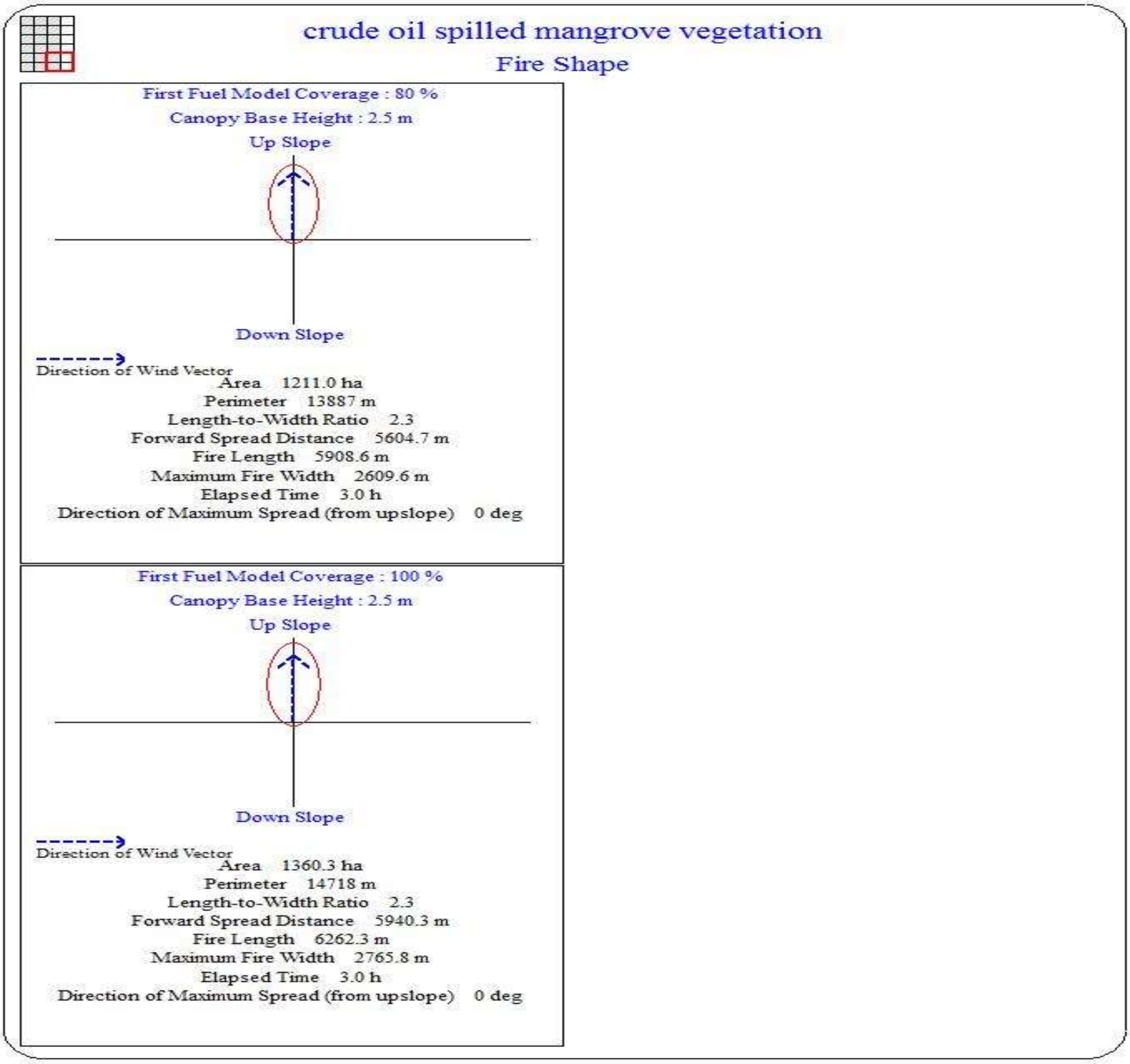

Figure 8: Fire shape characterization of combustion from 40% to 60% of fuel loading at various canopy base heights.

Figures 3 to 8 shows the fire shape at different fuel model change, canopy base height, wind vector direction, perimeter, length-to-width ratio, forward spread distance, fire length, max. fire width and elapsed time. It can be noticed that the higher the fuel model coverage, the faster and more spread the fire characteristics.

At 0% fuel loading, with a range of canopy base height of between 0.7 to 1.6 m, the Fire shape, depicted by the ring or oval shape, vertically, is less half the wind vector, with a combustion characterization as depicted in figure 4.36. The fire, at this fuel loading, is yet to be fully developed.

At 20% fuel loading, with a canopy base height of between 0.7 to 1.6 m, the fire shape, vertically, is half the wind vector, with combustion characterization as depicted in figure 8.

This trend, the rising or increase of the fire shape or size, increases with increase of the Fuel model coverage. However, the canopy base height does not affect the fire behavior.

At 60% fuel model loading, the fire shape, from the positive x-axis or from the horizontal, is at the same height as the wind vector.

Interestingly, at 80 – 100% fuel model loading, the fire, as represented by the oval or ring shape, had enveloped the wind vector. The canopy base height does not, yet, affect the fire behavior.

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3.2 Wind/Slope/Fire Direction Characterization

Wind and fire have the same directions (figure 3 to 13); to have it otherwise would have been a blatant violation of the laws of fluid flow dynamism.

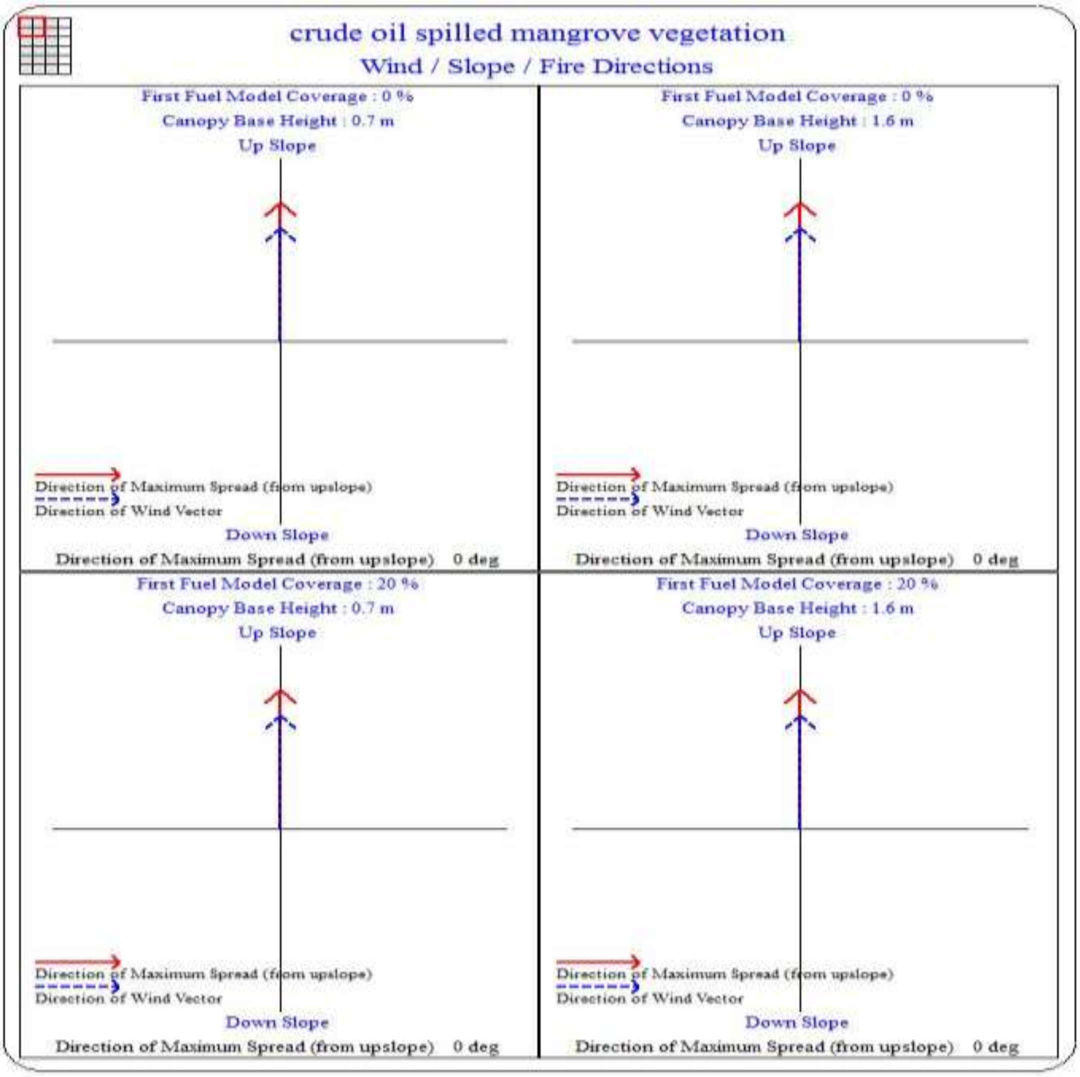

Figure 9:Wind/Smoke/Fire direction characterization of combustion from 0% fuel loading at various canopy base heights.

From the simulations (figure 9), it can be observed that the wind/slope and fire directions have the same direction as expected. So that, from the direction of the wind vector and slope, a fire fighter is able to predict the direction of the fire. It is observed that, in all cases (figure 9 to 13), though the fuel model coverage and the canopy base height changes, yet the direction of Maximum Spread (from upslope) and the direction of Wind Vector have the same direction.

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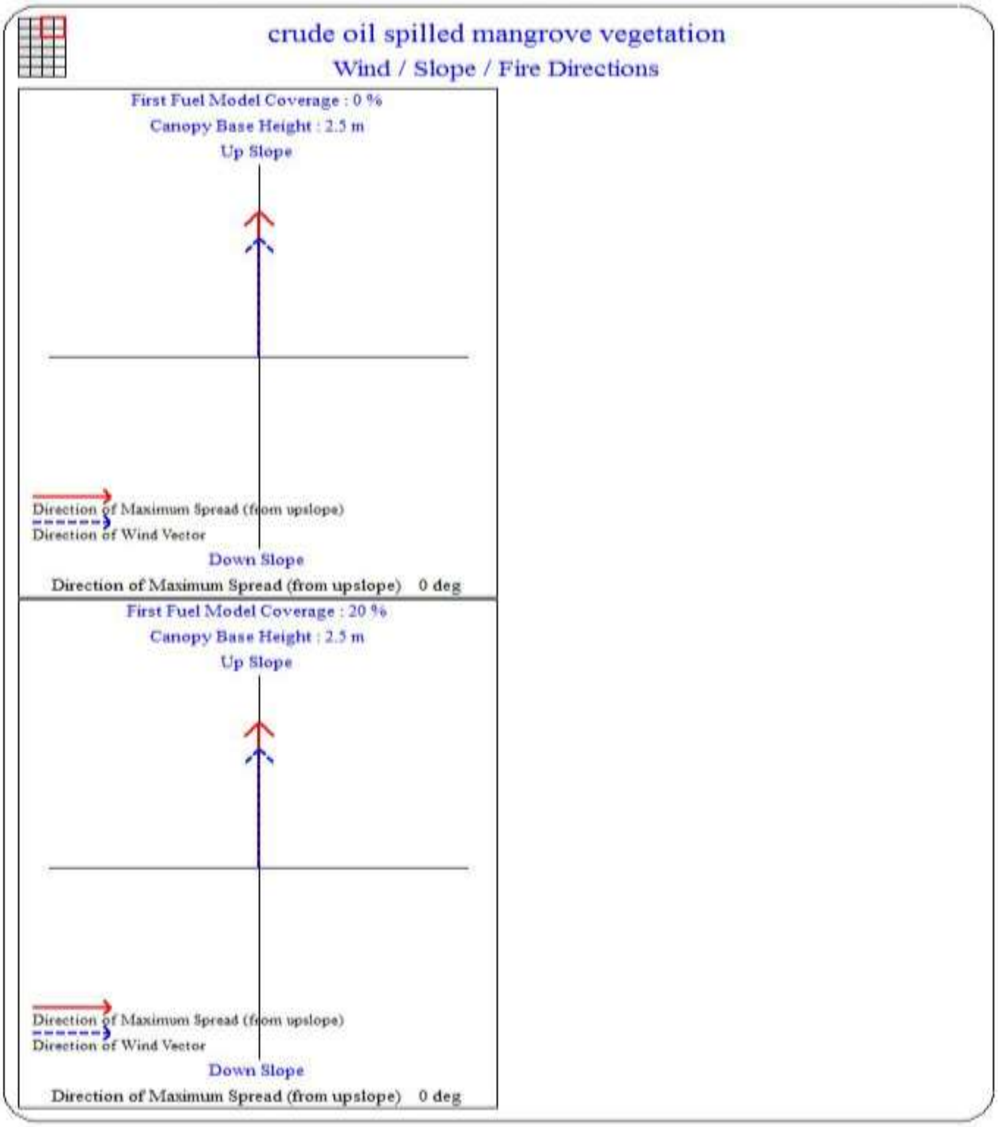

Figure 10: Wind/Smoke/Fire direction characterization of combustion from 0% to 20% fuel loading at various canopy base heights.

From the simulations (figure 10), it can be observed that the wind/slope and fire directions have the same direction as expected. So that, from the direction of the wind vector and slope, a fire fighter is able to predict the direction of the fire. It is observed that, in all cases (figure 9 to 13), though the fuel model coverage and the canopy base height changes, yet the direction of Maximum Spread (from upslope) and the direction of Wind Vector have the same direction.

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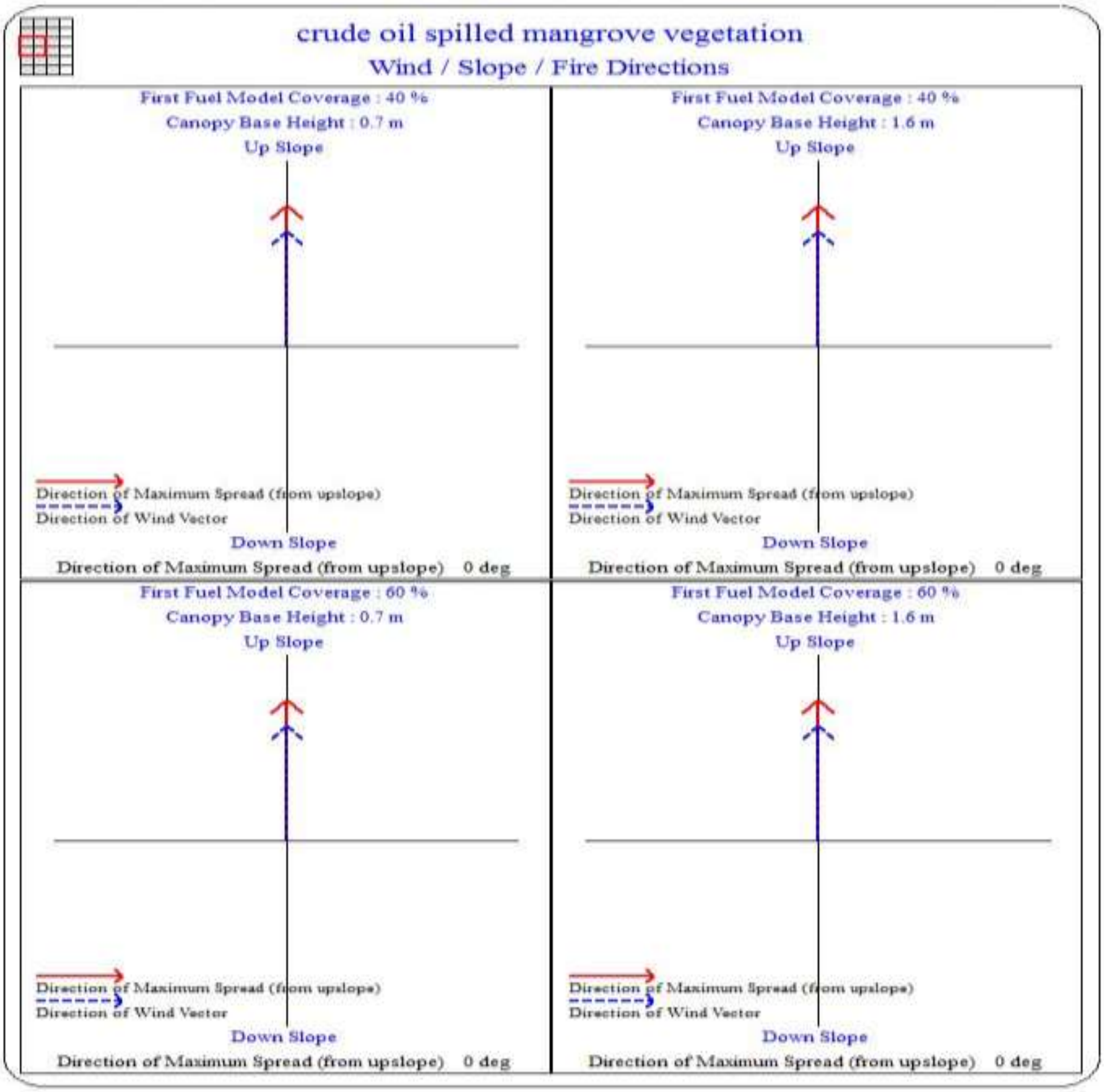

Figure 10: Wind/Smoke/Fire direction characterization of combustion from 0% to 60% fuel loading at various canopy base heights.

From the simulations (figure 10), it can be observed that the wind/slope and fire directions have the same direction as expected. So that, from the direction of the wind vector and slope, a fire fighter is able to predict the direction of the fire. It is observed that, in all cases (figure 9 to 13), though the fuel model coverage and the canopy base height changes, yet the direction of Maximum Spread (from upslope) and the direction of Wind Vector have the same direction.

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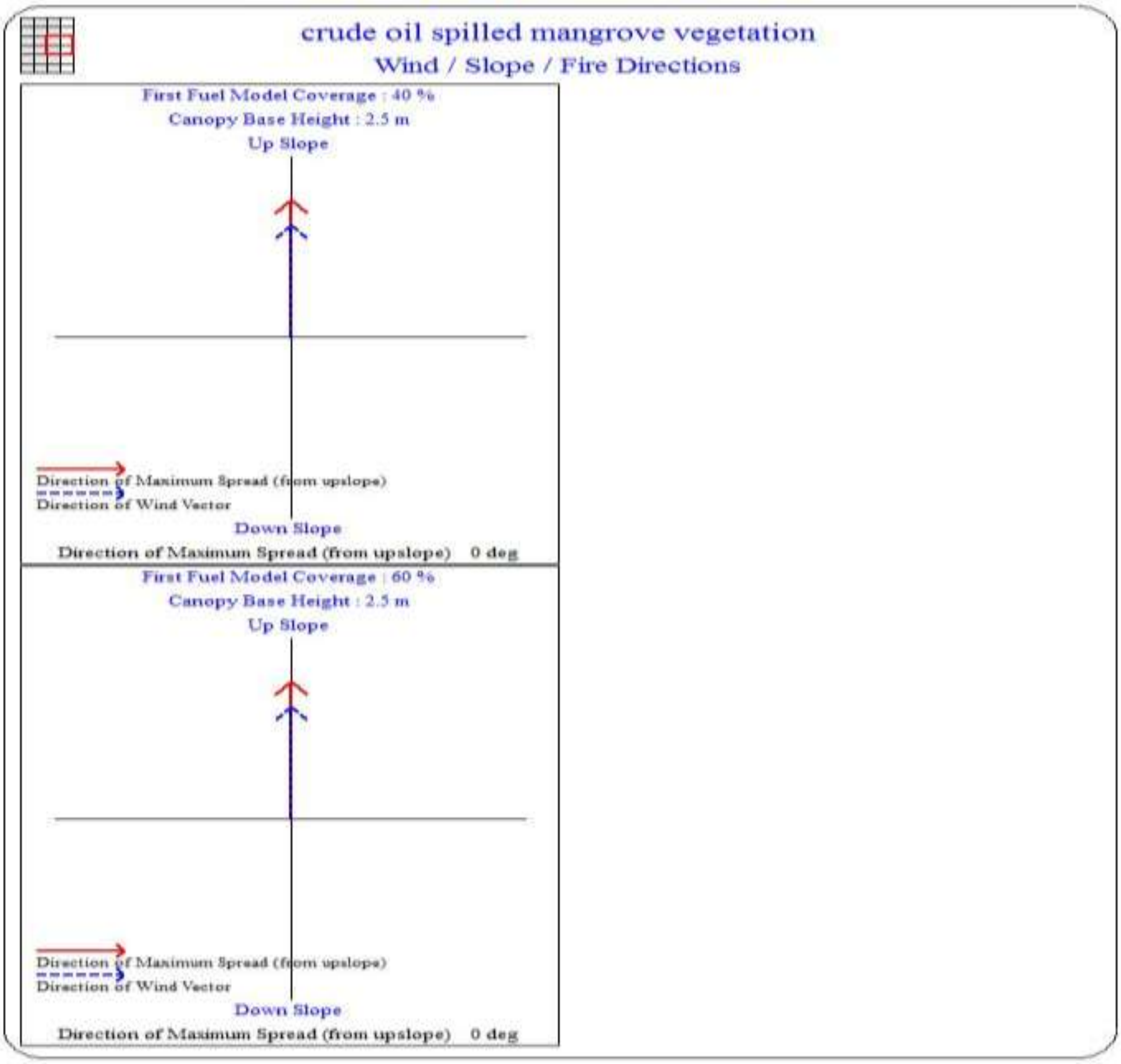

Figure 11: Wind/Smoke/Fire direction characterization of combustion from 0% to 60% fuel loading at various canopy base heights.

From the simulations (figure 11), it can be observed that the wind/slope and fire directions have the same direction as expected. So that, from the direction of the wind vector and slope, a fire fighter is able to predict the direction of the fire. It is observed that, in all cases (figure 3 to 13), though the fuel model coverage and the canopy base height changes, yet the direction of Maximum Spread (from upslope) and the direction of Wind Vector have the same direction.

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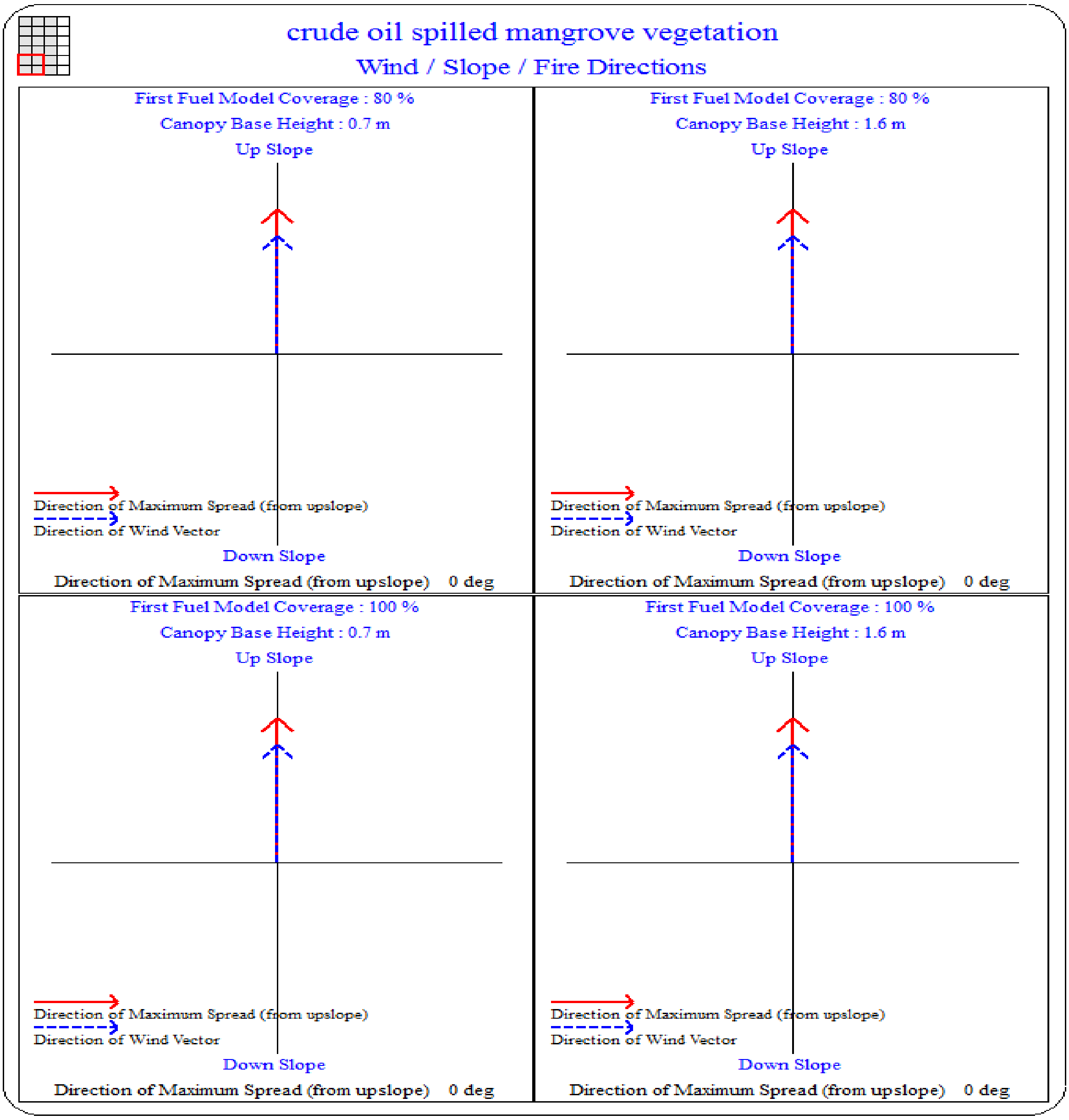

Figure 12: Wind/Smoke/Fire direction characterization of combustion from 80% to 100% fuel loading at various canopy base heights.

From the simulations (figure 12), it can be observed that the wind/slope and fire directions have the same direction as expected. So that, from the direction of the wind vector and slope, a fire fighter is able to predict the direction of the fire. It is observed that, in all cases (figure 3 to 13), though the fuel model coverage and the canopy base height changes, yet the direction of Maximum Spread (from upslope) and the direction of Wind Vector have the same direction.

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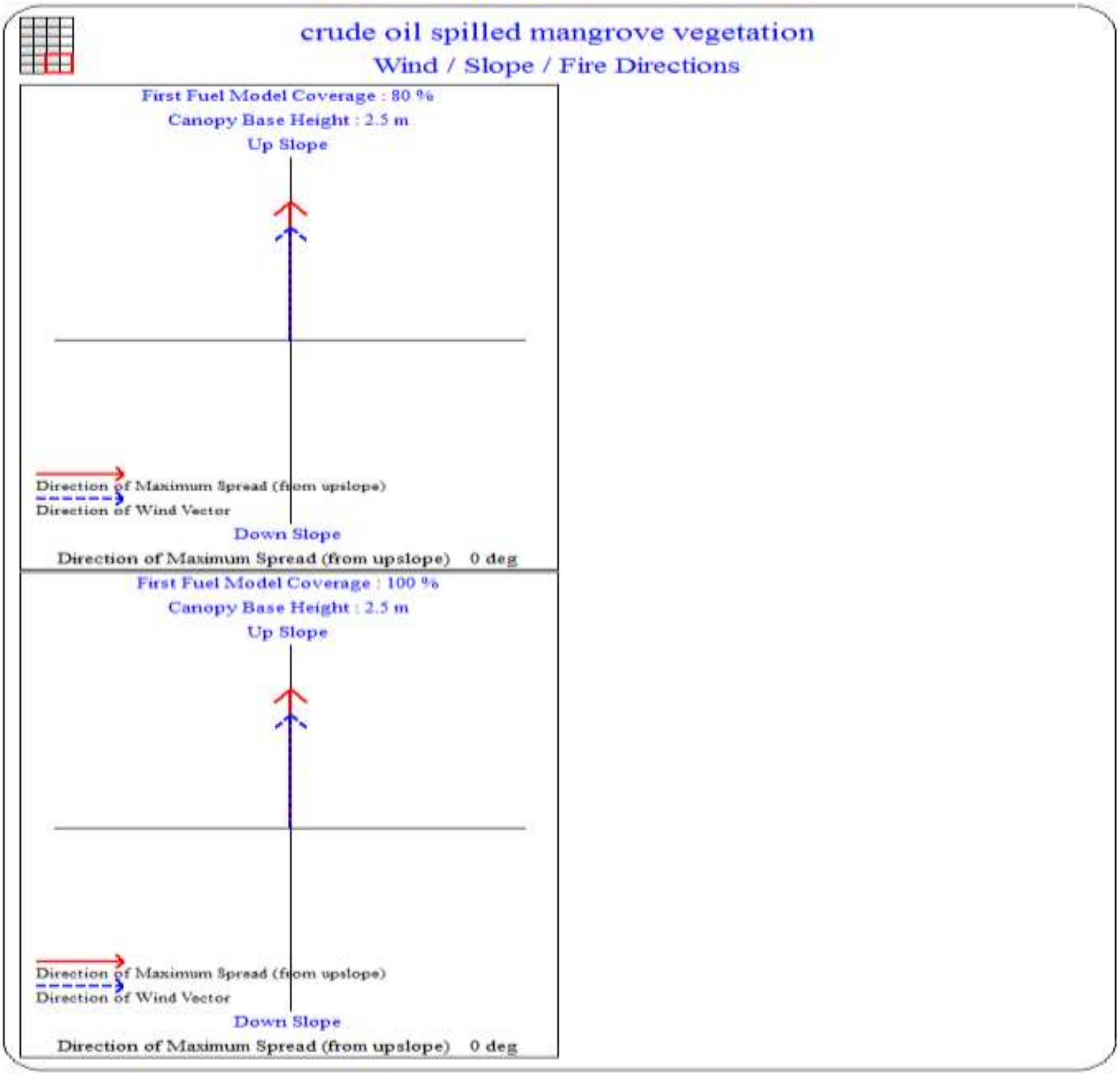

Figure 13: Wind/Smoke/Fire direction characterization of combustion from 80% to 100% fuel loading at various canopy base heights continued.

From the simulations (figure 3 to 13), it can be observed that the wind/slope and fire directions have the same direction as expected. So that, from the direction of the wind vector and slope, a fire fighter is able to predict the direction of the fire. It is observed that, in all cases (figure 3 to 14), though the fuel model coverage and the canopy base height changes, yet the direction of Maximum Spread (from upslope) and the direction of Wind Vector have the same direction.

4.0 CONCLUSION

The risk assessment resultant from this study showed that should there be a fire incident, the havoc to be wrecked on the adjoining community and the immediate community could be devastating. The simulations were carried out by keeping Elapse time and length-to-width ratio constant at 3 hours and 2.3, respectively. The numerical risk modeling showed that over 200, 000 lives and over 150,000 houses, wildlife and even aquatic lives and billions of dollars of properties could be destroyed by fire. The numerical risk assessment quantified showed that the following communities could be at risk: the federal University of Petroluem Resources, Effurun, Iteregbe, Ogbomro, Okorikpereh, parts of Okuokoko, parts of Agbarho. From the study, and its simulations and investigative study, it is strongly recommended that a fire station be established in this vicinity to mitigate a possible fire outbreak.

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Table 1: Summary of numerical risk assessment modeling results output

FFMC(%)	CBH(m)	A (ha)	P(m)	L/w (-)	FSD (m)	FL (m)	MFW (m)	ET(h)
0	0.7	168.9	5168	2.3	2093	2206.5	974.7	3
0	1.6	168.9	5168	2.3	2093	2206.5	974.7	3
0	2.5	168.9	5186	2.3	2093	2206.5	974.7	3
20	0.7	333.8	7291	2.3	2942.1	3102.2	1370.1	3
20	1.6	333.8	7291	2.3	2942.6	3102.2	1370.1	3
20	2.5	333.8	7291	2.3	2942.6	3102.2	1370.1	3
40	0.7	580.7	9617	2.3	3881.2	4091.7	1807.1	3
40	1.6	580.7	9617	2.3	3881.2	4091.7	1807.1	3
40	2.5	580.7	9617	2.3	3881.2	4091.7	1807.1	3
60	0.7	898.4	11961	2.3	4827.6	5089.3	2247.7	3
60	1.6	898.4	11961	2.3	4827.6	5089.3	2247.7	3
60	2.5	898.4	11961	2.3	4827.6	5089.3	2247.7	3
80	0.7	1211	13887	2.3	5604.7	5908.6	2609.6	3
80	1.6	1211	13887	2.3	5604.7	5908.6	2609.6	3
80	2.5	1211	13887	2.3	5604.7	5906.7	2609.6	3
100	0.7	1360.3	14718	2.3	5940.3	6262.3	2765.8	3
100	1.6	1360.3	14718	2.3	5940.3	6262.3	2765.8	3
100	2.5	1360.3	14718	2.3	5940.3	6262.3	2765.8	3

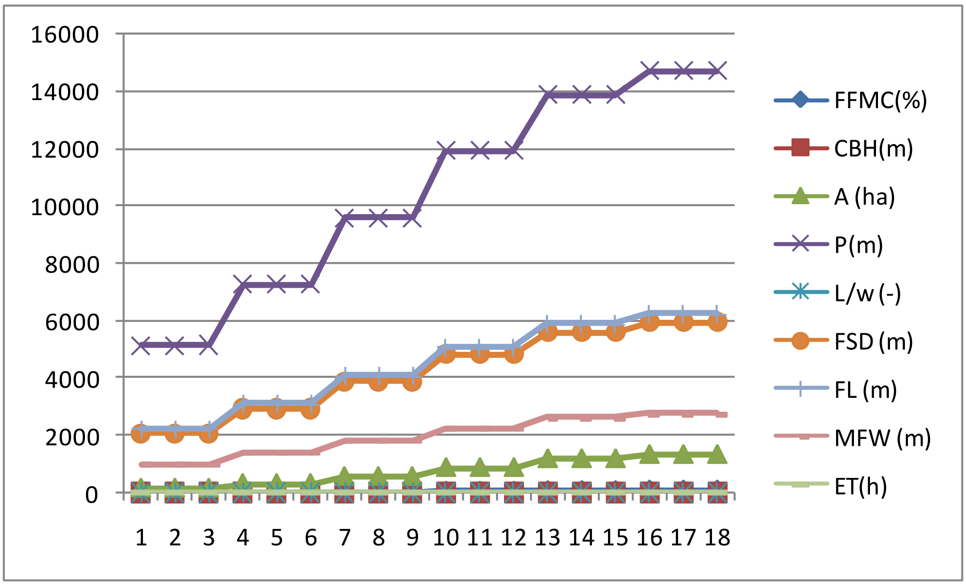

Figure 14. Diagramed scatter plots for all the results

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