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Supplementary Material

Physics-based simulations of grassfire propagation on sloped terrain at field scale: motivations, model reliability, rate of spread and fire intensity

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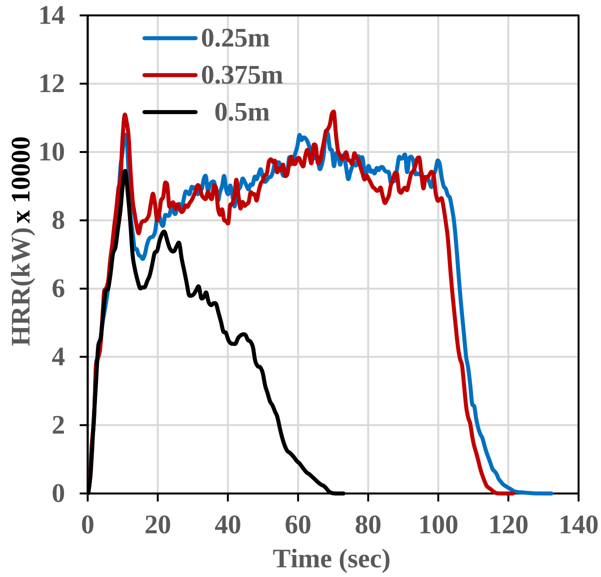
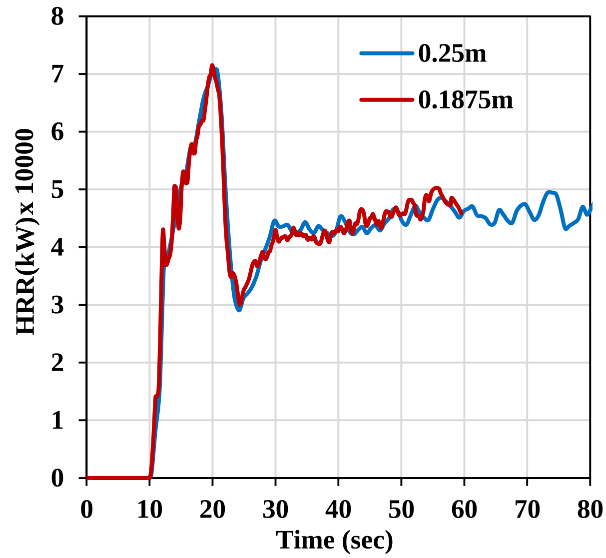
Appendix A: Supplementary document

Table S1: Thermo-physical, pyrolysis and combustion parameters for grassfire modelling

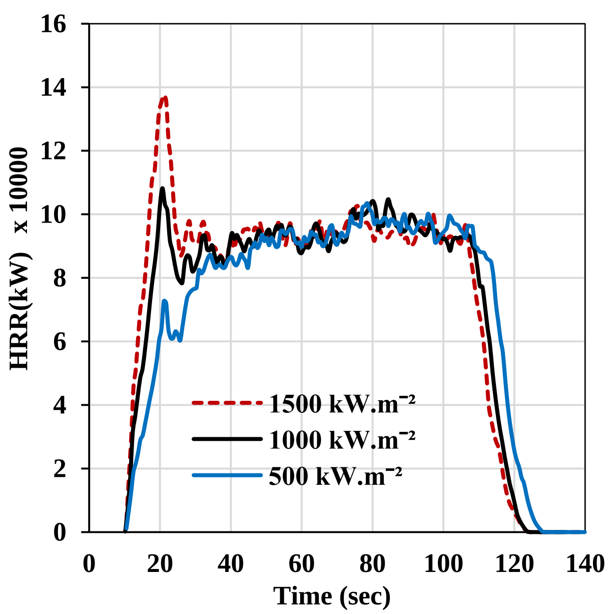
Input parameters	**Used values**	**Source and reason**
Heat of combustion	16400 $kJ.kg^{-1}$	Blustem grass (Overholt et al., 2014)
Soot yield	0.008 g/g	White pine (Australian Radiata pine) (Abu Bakar, 2015)
Vegetation drag coefficient	0.125	assuming vegetation elements are spherical (Morvan and Dupuy, 2004)
Vegetation load	0.283 $kg.m^{-2}$	Mell et al, 2007 - experimental
Vegetation height	0.21 m	Mell et al, 2007 - experimental
Vegetation moisture content	0.065	Mell et al, 2007 – experimental,
Surface-to-volume ratio of vegetation	9770 m^{-1}	Mell et al, 2007 - experimental
Vegetation char fraction	0.17	Average of Mell et al., 2007 & Blustem grass (Overholt et al, 2014)
Vegetation element density	440 $kg.m^{-3}$	White pine (Australian Radiata pine) (Abu Bakar, 2015)
Ambient temperature	32°C	Mell et al, 2007 -experimental
Relative humidity	40 %	Mell et al, 2007
Emissivity	0.99	Mell et al, 2007
Pyrolysis Temperature	400-500K	Morvan and Dupuy,2004
Degree of curing	100	Assuming vegetation100% cured
Vegetation heat of pyrolysis (Δh_{pyr})	200 $kJ.kg^{-1}$	White pine (Australian Radiata pine) (Abu Bakar, 2015)
Maximum mass loss rate	0.15 ($kg.s^{-1}.m^{-3}$)	Mell et al, 2007 - experimental, Maximum amount of fuel allowed to be pyrolysed



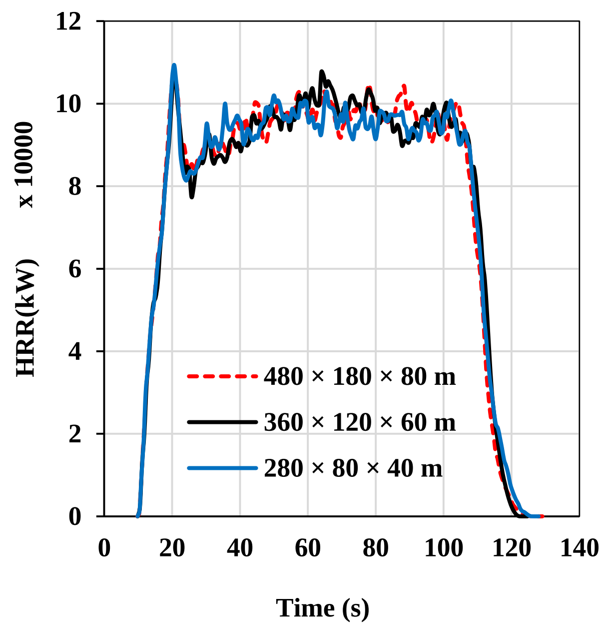
(a) Grid sensitivity - 0° slope at $6 m.s^{-1}$



(b) Grid sensitivity, –10° slope at $3 m.s^{-1}$



(c) Ignition line Intensity- 0° slope at $6 m.s^{-1}$



HRR vs time

Figure S1: Convergence in relation to Heat release rate (HRR) vs time: (a) Grid sensitivity for 0° slope at $6 m.s^{-1}$, (b) Grid sensitivity for –10° slope at $3 m.s^{-1}$, (c) Ignition line Intensity and (d) Domain sensitivity.

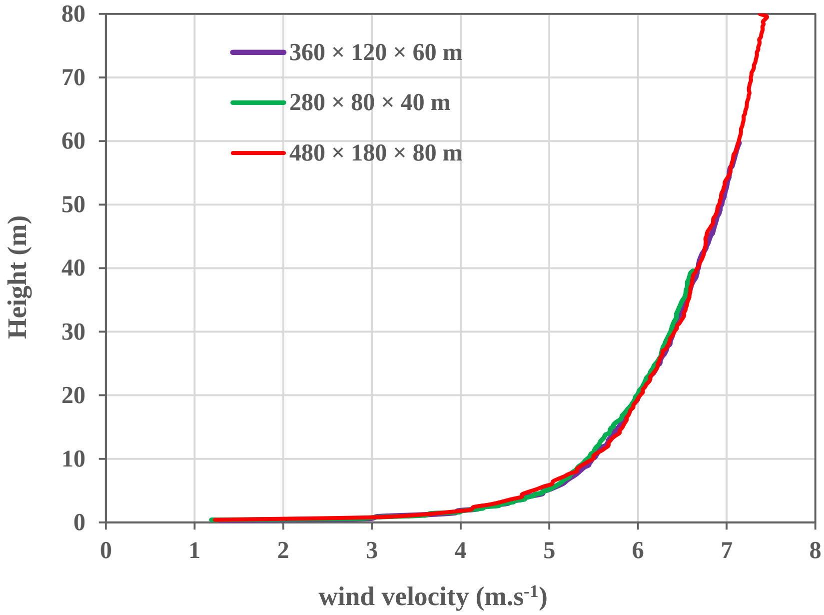


Figure S2: The wind profiles vs height for 0° slope at driving wind velocity of 6m.s^{-1} for the three domains, taken at the inlet of burnable gras plot (at +2m, immediately before the ignition line).

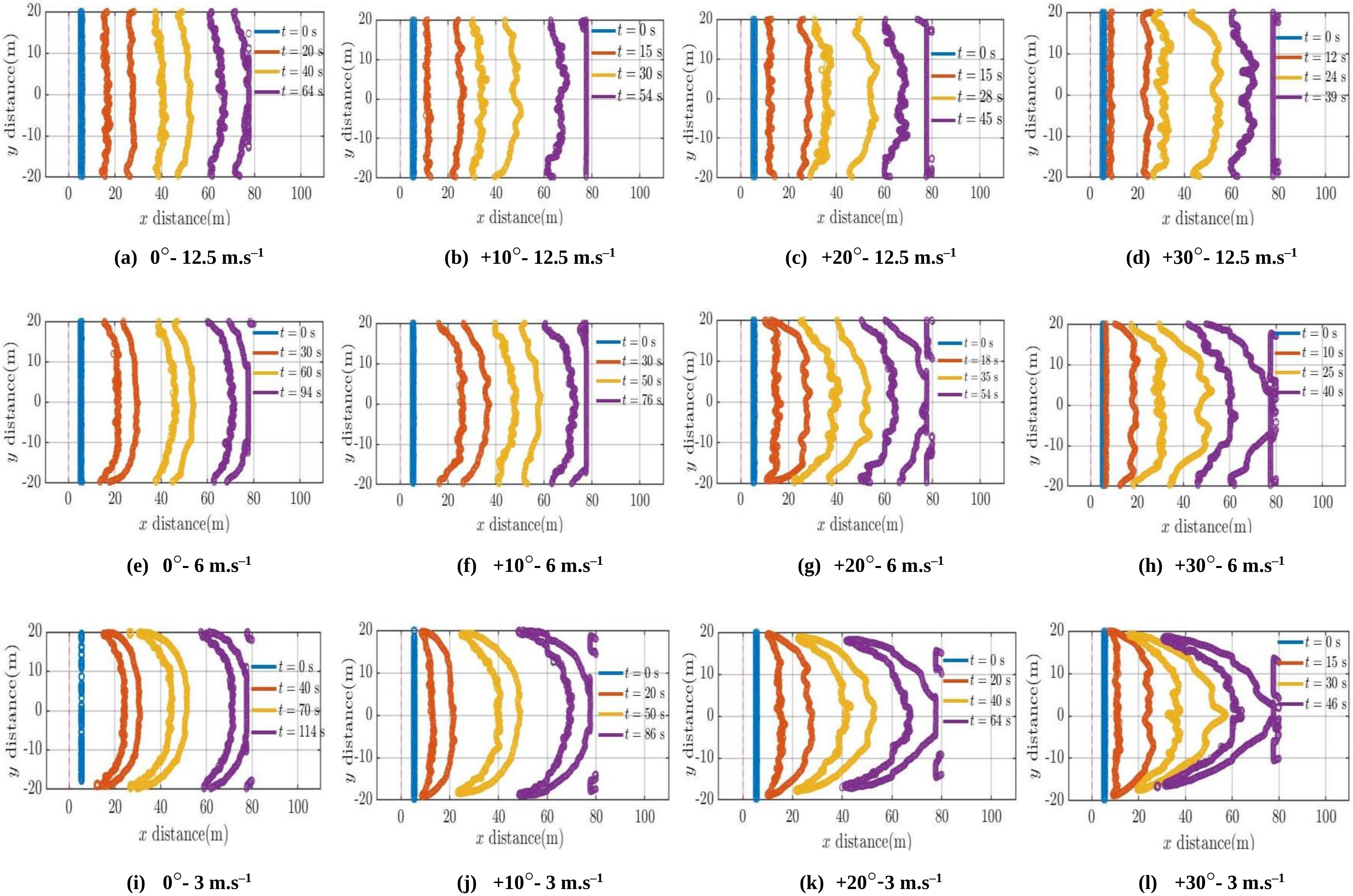
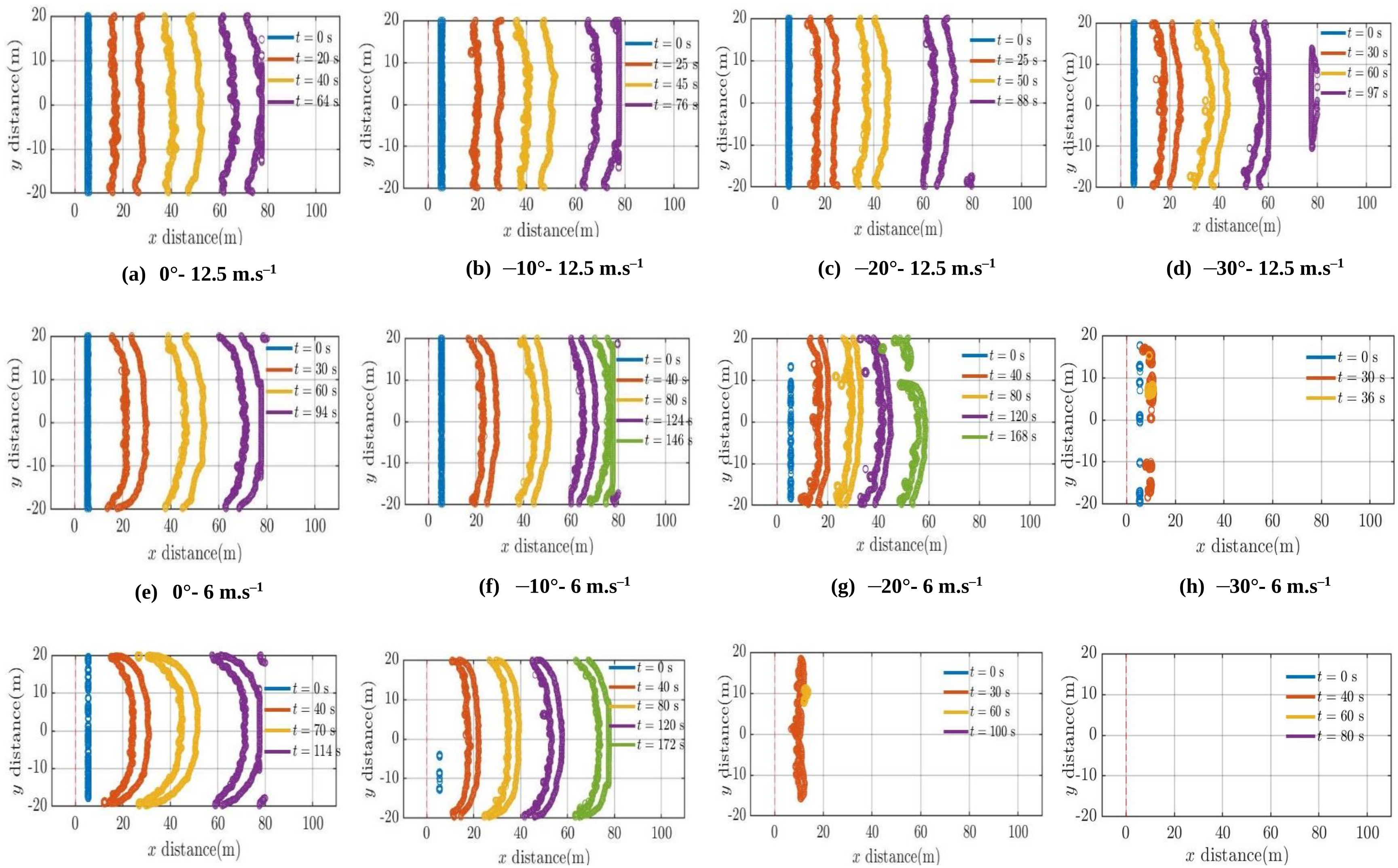


Figure *S3*: Progression of isochrones, upslopes 0° +10°, +20°, +30° at wind velocities: (a–d) 12.5 $m.s^{-1}$, (e–h) 6 $m.s^{-1}$, (i–l) 3 $m.s^{-1}$

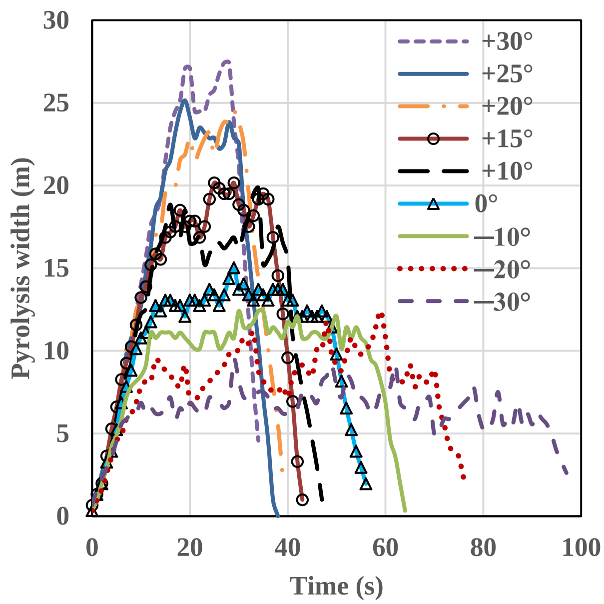


(a) 0°- 12.5 m.s^{-1} **(b) –10°- 12.5 m.s^{-1}** **(c) –20°- 12.5 m.s^{-1}** **(d) –30°- 12.5 m.s^{-1}**

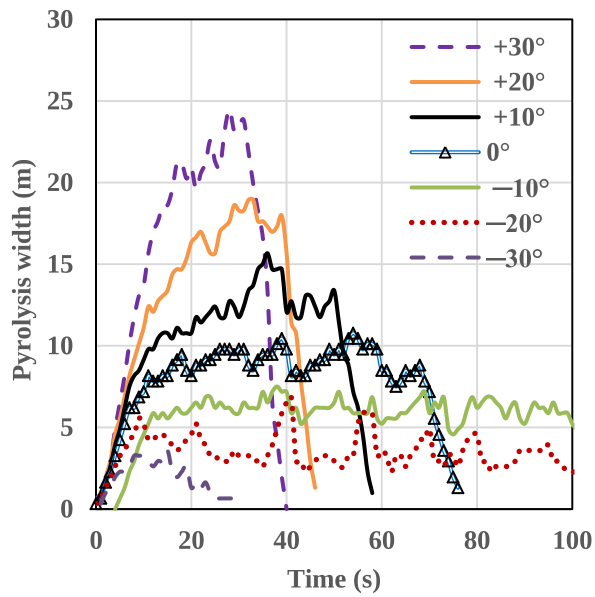
(e) 0°- 6 m.s^{-1} **(f) –10°- 6 m.s^{-1}** **(g) –20°- 6 m.s^{-1}** **(h) –30°- 6 m.s^{-1}**

(i) 0°- 3 m.s^{-1} **(j) –10°- 3 m.s^{-1}** **(k) –20°- 3 m.s^{-1}** **(l) –30°- 3 m.s^{-1}**

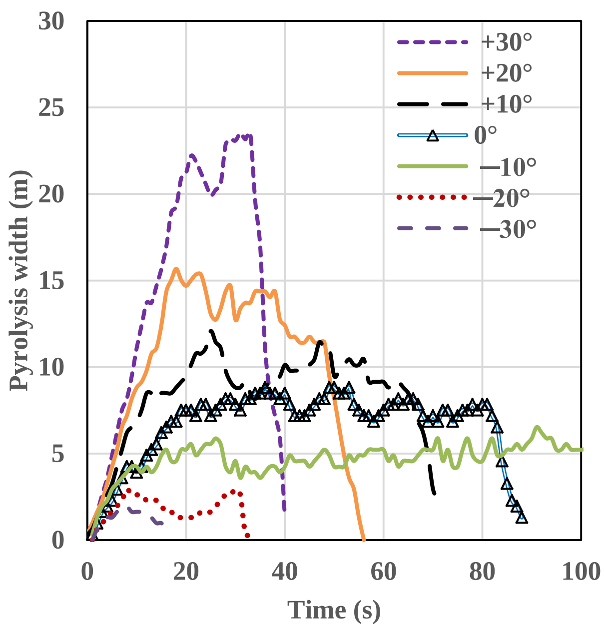
Figure *S4*: Progression of isochrones, downslopes 0°, –10°, –20°, –30° at wind velocities: (a–d) 12.5 m.s^{-1}; (e–h) 6 m.s^{-1}; (i–l) 3 m.s^{-1}



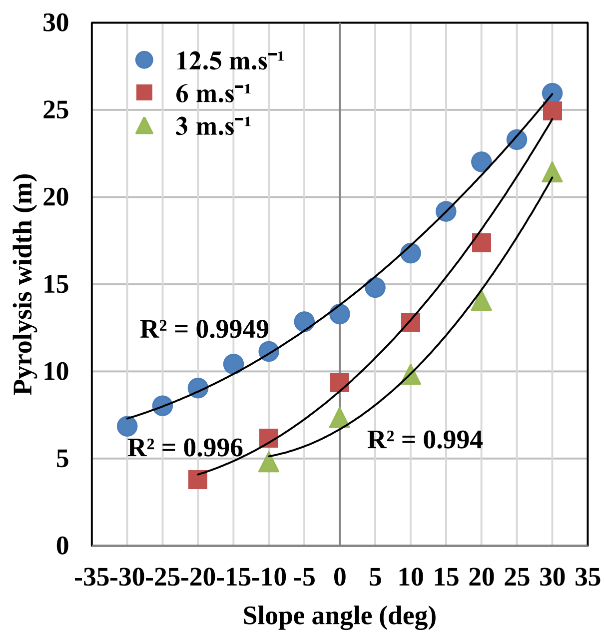
(a) Pyrolysis width vs time –12.5 m.s^{-1}



(b) Pyrolysis width vs time– 6 m.s^{-1}

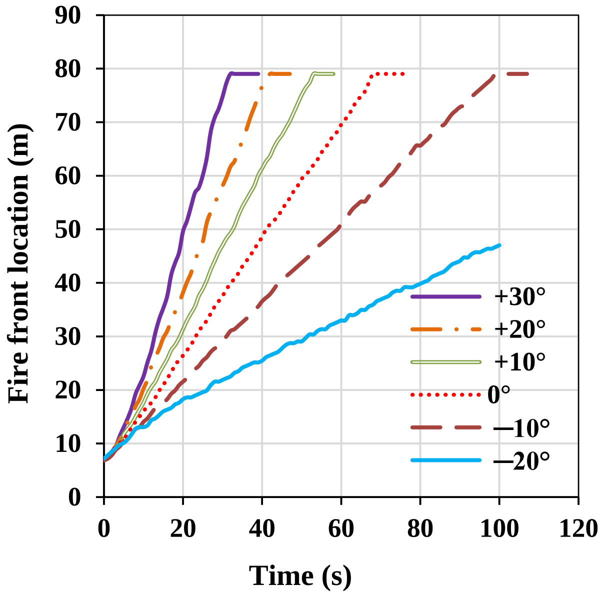


(c) Pyrolysis width vs time – 3 m.s^{-1}

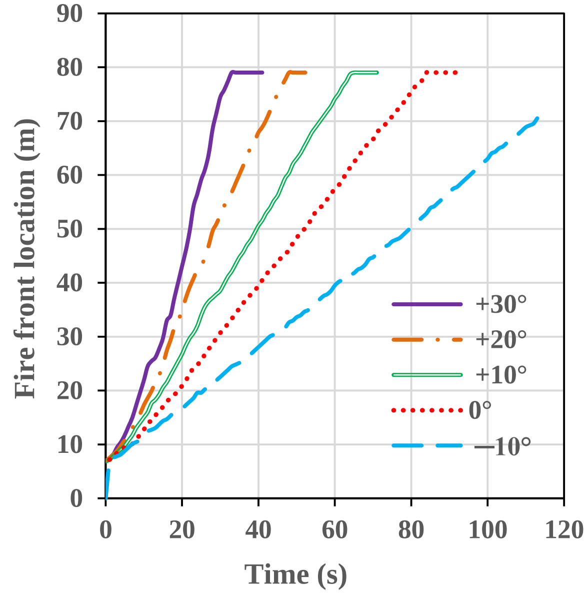


(d) pyrolysis width vs slope angle

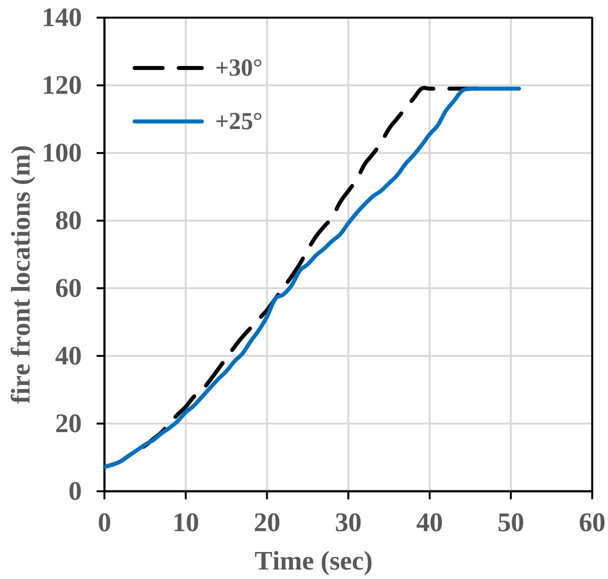
Figure S5: Pyrolysis width vs time: upslope and downslopes (a) at 12.5 m.s^{-1}, (b) at 6 m.s^{-1}, (c) at 3 m.s^{-1}; (d) quasi-steady pyrolysis width vs slope angles, at 12.5, 6 and 3 m.s^{-1} (for +30° and +25° at 12.5 m.s^{-1}, and +30° at 6 m.s^{-1} cases, quasi-steady values are derived from longer grass plot simulations)



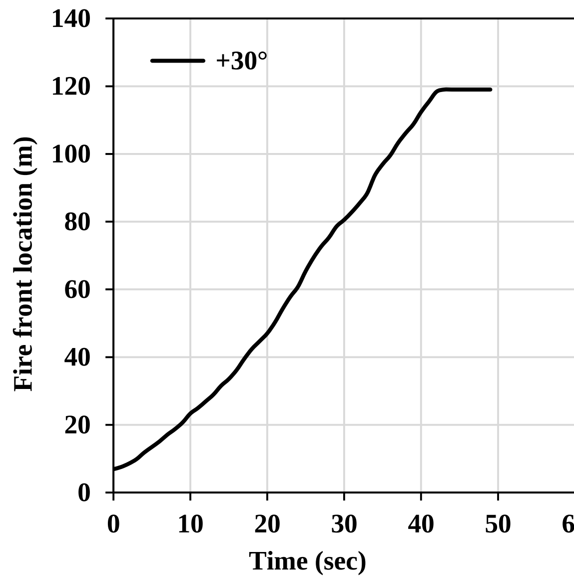
(a) firefront, up and downslopes - 6m.s^{-1}



(b) firefront, up and downslopes - 3m.s^{-1}

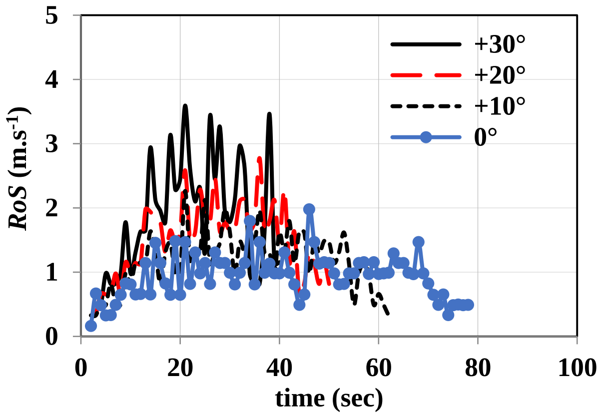


(c) Fire front - extended grass plot, 12.5 m.s^{-1},

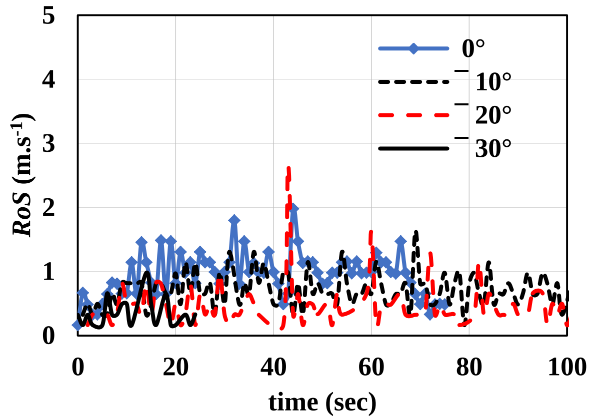


(d) Fire front - extended grass plot, 6 m.s^{-1}

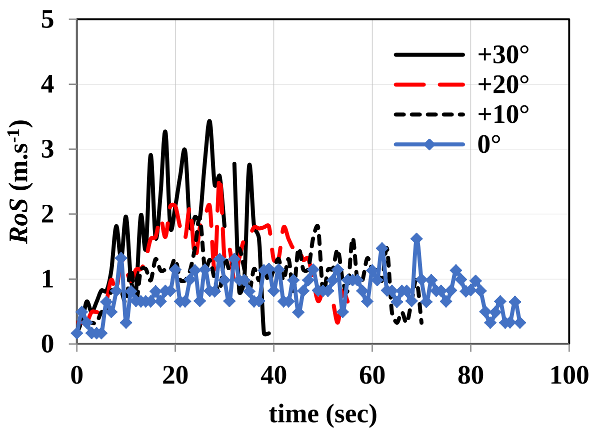
Figure S6**: (a-b)** Firefront locations (m) vs time (sec) for upslopes and downslopes, at wind velocities 6 m.s^{-1} and 3m.s^{-1}, **(c-d)** Fire front vs time with burnable grass plot extended to 120 m in the x- direction: +30°, +25° at 12.5 m.s^{-1} and +30° at 6 m.s^{-1}



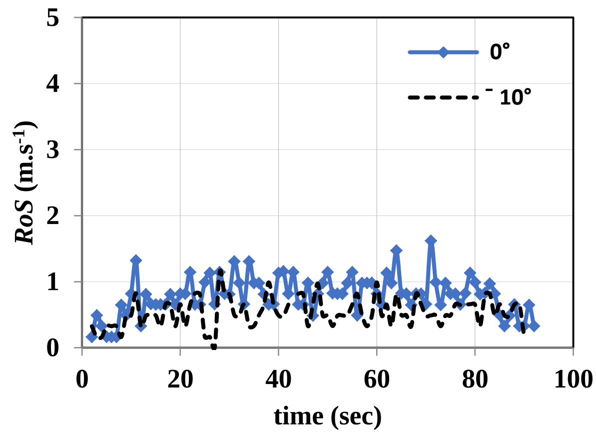
(a) Dynamic *RoS*- upslope, 6m.s^{-1}



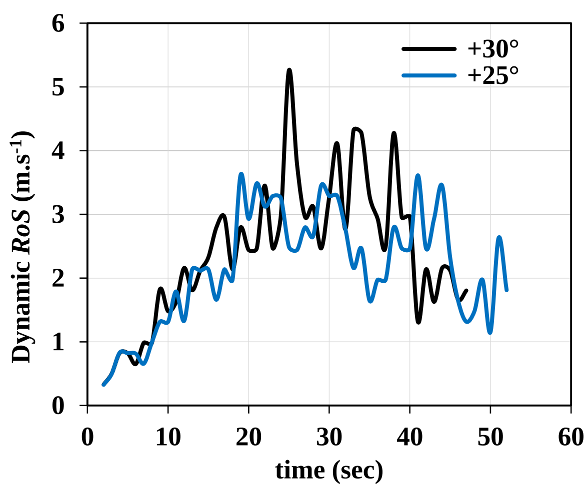
(b) Dynamic *RoS*- downslope, 6m.s^{-1}



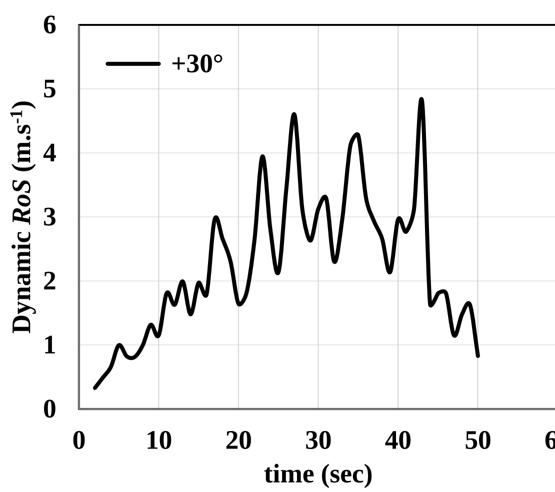
(c) Dynamic *RoS* - upslope, 3m.s^{-1}



(d) Dynamic *RoS*- downslope, 3m.s^{-1}

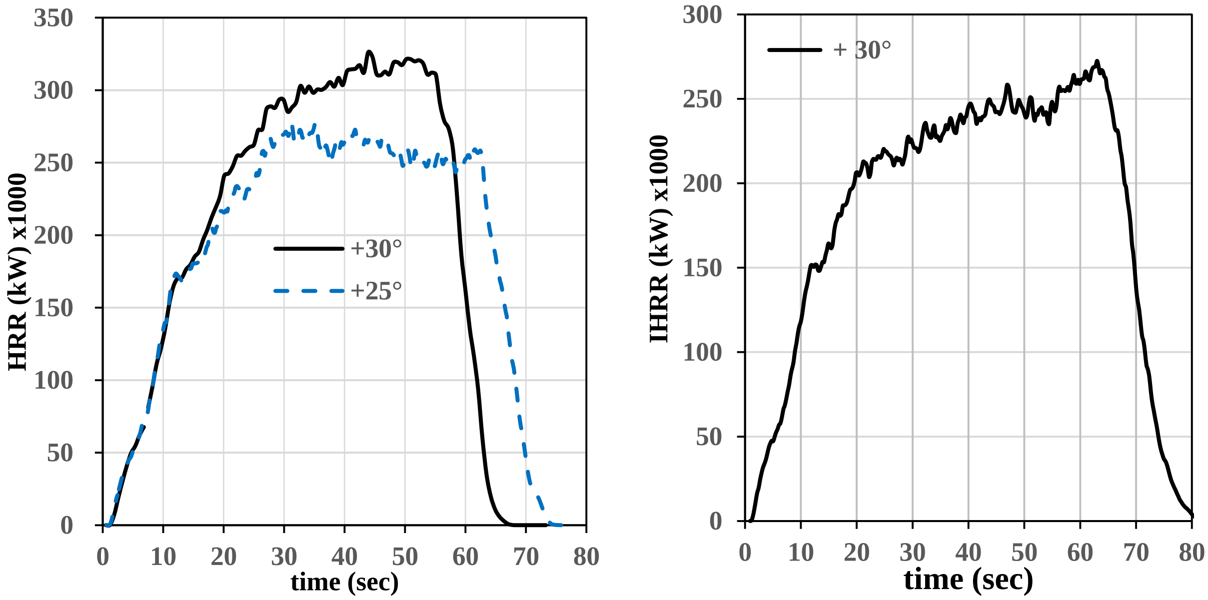


(e) Dynamic *RoS*- extended plot, 12.5 m.s^{-1}



f) Dynamic *RoS*- extended plot, 6 m.s^{-1}

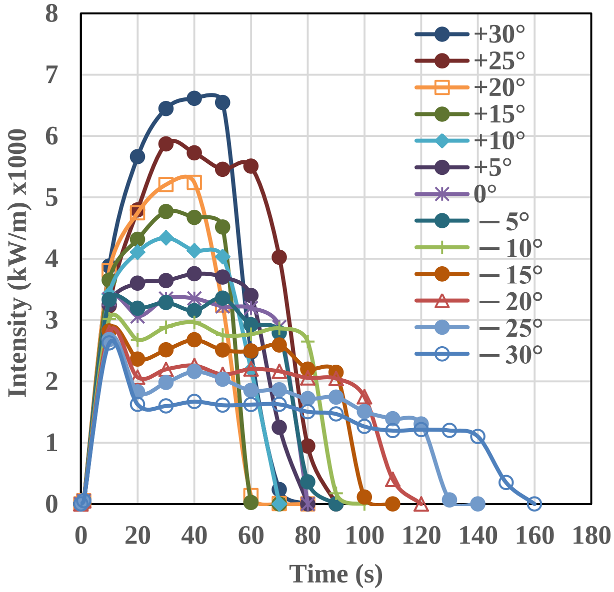
Figure S7: Dynamic *RoS* vs time: (a) upslopes at 6 m.s^{-1}, (b) downslopes at 6 m.s^{-1}; (c) upslopes at 3 m.s^{-1}, (d) downslopes at 3 m.s^{-1}; (e) with 120m long grass plot, for +30°, +25° at 12.5m.s^{-1} and (f) with 120m long grass plot, for +30° at 6 m.s^{-1}.



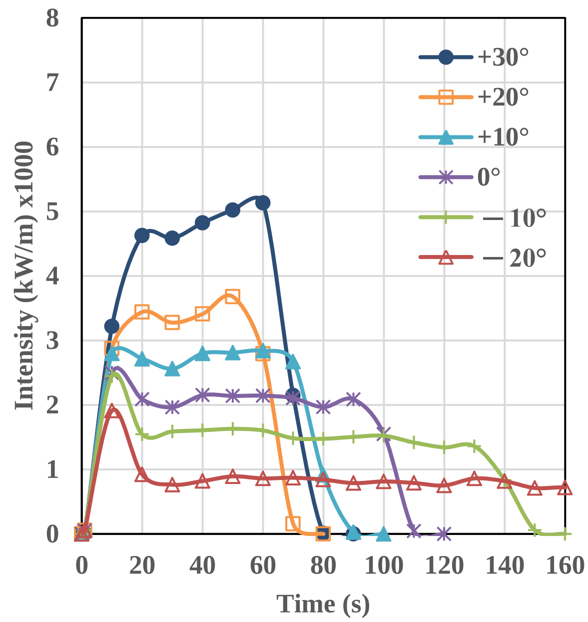
(a) HRR vs time, at 12.5m.s^{-1}

(b) HRR vs time, at 6m.s^{-1}

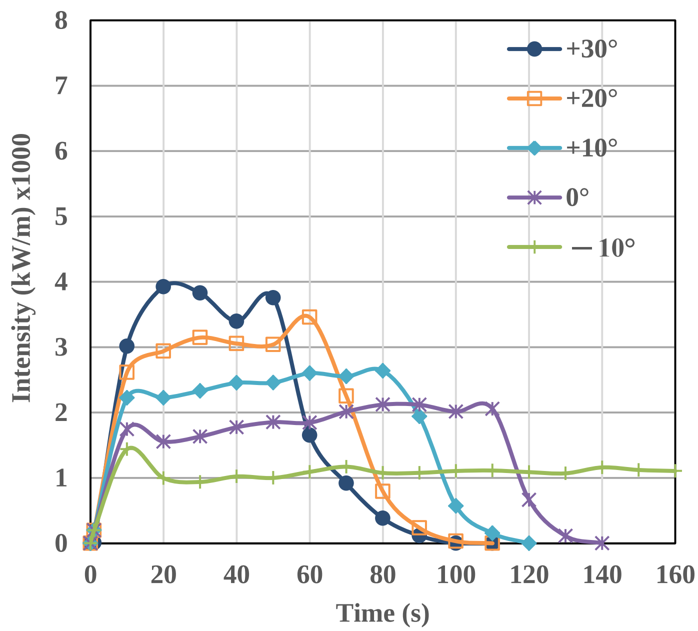
Figure S8**:** Heat release rate (HRR) as a function of time with longer domain (burnable grass plot extended to 120m in the x- direction) for; (a) +30°, +25° slopes at 12.5m.s^{-1} wind velocity (b) +30° slope at 6m.s^{-1} wind velocity.



(a) Intensity vs time – 12.5m.s^{-1}



(b) Intensity vs time - 6m.s^{-1}



(c) Intensity vs time- 3m.s^{-1}

***Figure S9*:** Fire Intensity as a function of time at wind velocities of: (a) 12.5m.s^{-1}, (b) 6m.s^{-1}, (c) 3 m.s^{-1}. (for +30° at 12.5 m.s^{-1} and 6 m.s^{-1} cases, the values are derived from longer grass plot simulation results)

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REFERENCES

1. Abu Bakar AS (2015), Characterization of Fire Properties for Coupled Pyrolysis and Combustion Simulation and Their optimised Use. PhD Thesis. Victoria University. http://vuir.vu.edu.au/31007/
2. Mell W, Jenkins MA, Gould J, Cheney P (2007), A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire*, **16,** 1, 1-22.
3. Morvan D, Dupuy J (2004), Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation. *Combustion and flame*. **138**, 3, 199-210.
4. Overholt K, Cabrera J, Kurzawski A, Koopersmith M, Ezekoye OA (2014), Characterization of fuel properties and fire spread rates for little bluestem grass. *Fire Technology*, 2014. 50, 1, 9-38.

WFDS Simulation script for a case (upslope10 - 6m/sec)

Wildland–Urban Interface Fire Dynamics Simulator (WFDS) version svn 9977 (developed by Dr. Ruddy Mell at US Forest Department) is used here. This is compatible with FDS (Fire Dynamic Simulator) version 6.0 released by National Institute of Standards and Technology (NIST), USA. The source code is supplied by Dr. Mell.

```
&HEAD CHID='upslope10-6msec', TITLE='upslope 10deg, burnable grass 40mx80m ,VEL=-6.0m/sec' /
&TIME T_END=660/,
&MISC PROJECTION=.TRUE.,WIND_ONLY=.FALSE.,TMPA=32.,GVEC=-1.703,0.0,-9.661,/
INITIAL_UNMIXED_FRACTION=0/ RESTART=.TRUE.

&DUMP
DT_SLCF=1.0,DT_BNDF=1,DT_ISOF=1,DT_PL3D=50,PLOT3D_QUANTITY(1:5)='TEMPERATURE','U-
VELOCITY','V-VELOCITY','W-VELOCITY','HRRPUV',DT_DEVC=1,
DT_DEVC_LINE=300,/UVW_TIMER(1)=405./

---for 16 meshes
&MESH IJK=60,120,60, XB=-150,-90,-60,60,0,60 /mesh 1
&MESH IJK=180,80,120, XB=-90,0,-20,20,0,60 /mesh 2
&MESH IJK=80,160,240,XB=0,20,-20,20,0,60 /mesh 3,
&MESH IJK=80,160,240,XB=20,40,-20,20,0,60 /mesh 4,
&MESH IJK=80,160,240,XB=40,60,-20,20,0,60 /mesh 5,
&MESH IJK=80,160,240,XB=60,80,-20,20,0,60 /mesh 6,
&MESH IJK=140,80,120, XB=80,150,-20,20,0,60 /mesh 7,
&MESH IJK=60,120,60, XB=150,210,-60,60,0,60 /mesh 8
&MESH IJK=120,80,120,XB=-90,-30,-60,-20,0,60 /mesh 9
&MESH IJK=120,80,120,XB=-30,30,-60,-20,0,60 /mesh 10
&MESH IJK=120,80,120,XB=30,90,-60,-20,0,60 /mesh 11
&MESH IJK=120,80,120,XB=90,150,-60,-20,0,60 /mesh 12
&MESH IJK=120,80,120,XB=-90,-30,20,60,0,60 /mesh 13
&MESH IJK=120,80,120,XB=-30,30,20,60,0,60 /mesh 14
&MESH IJK=120,80,120,XB=30,90,20,60,0,60 /mesh 15
&MESH IJK=120,80,120,XB=90,150,20,60,0,60 /mesh 16

-- Boundary conditions
&SURF ID='INFLOW',PROFILE='ATMOSPHERIC',Z0=10,PLE=0.143,VEL=-6.00/,RAMP_V='rampv' /
```

```
&VENT XB = -150,-150, -60,60,0,60, SURF_ID = 'INFLOW',N_EDDY=200,L_EDDY=6.0,VEL_RMS=0.6 /

&VENT XB =210,210, -60,60,0,60, SURF_ID = 'OPEN' /outflow
&VENT XB = -150,210, -60,-60,0,60, SURF_ID = 'MIRROR' /RIGHT SIDE
&VENT XB = -150,210, 60,60,0,60, SURF_ID = 'MIRROR' /LEFT SIDE
&VENT XB = -150,210, -60,60,60,60, SURF_ID = 'OPEN' /TOP

!--devices simulating thermocouples on OBST
&OBST XB =80,80,-0.25,0.25,1.25,1.75, SURF_ID='INERT'/
&DEVC XYZ=80,0,1.5, ID='RADI-FRONT', IOR=-1, QUANTITY='RADIATIVE HEAT FLUX'/
&DEVC XYZ=80,0,1.5, ID='CONV-FRONT',IOR=-1, QUANTITY='CONVECTIVE HEAT FLUX'/

&REAC ID='WOOD'
    FUEL='WOOD'
    FYI='Ritchie, et al., C_3.4 H_6.2 O_2.5, Overholt 2014, dHc = 16.4MW/kg, Ariza, 2016 soot .008 pine'
    SOOT_YIELD = 0.008
    O       = 2.5
    C       = 3.4
    H       = 6.2
    HEAT_OF_COMBUSTION = 16400 /

&SPEC ID='WATER VAPOR' /

- Boundary fuel GRASS C064, VEG_MOISTURE derived from AS3959 formula for grassland
&SURF ID  = 'GRASS', VEGETATION = .TRUE.,VEG_DRAG_COEFFICIENT = 0.125, VEG_LOAD =
0.283,VEG_HEIGHT = 0.21,VEG_MOISTURE  = 0.065,VEG_SV = 9770, VEG_CHAR_FRACTION=
0.17, VEG_DENSITY = 440,EMISSIVITY  = 0.99, VEG_DEGRADATION =
'LINEAR',FIRELINE_MLR_MAX = 0.15, VEG_H_PYR= 200, VEG_HCONV_CYLRE = .TRUE., RGB =
122,117,48 ,ROUGHNESS=0.9/

!-- BURN GRASS
&VENT XB=5,20,-20,20,0,0,SURF_ID='GRASS' /Grass plot within 3
&VENT XB=20,40,-20,20,0,0,SURF_ID='GRASS' /Grass plot 4
&VENT XB=40,60,-20,20,0,0,SURF_ID='GRASS' /Grass plot 5
&VENT XB=60,80,-20,20,0,0,SURF_ID='GRASS' /Grass plot 6

!-- NO BURN GRASS
```

```
&SURF ID = 'NO BURN GRASS',VEGETATION = .TRUE.,VEG_NO_BURN  =
.TRUE.,VEG_DRAG_COEFFICIENT = 0.125,VEG_LOAD = 0.283, VEG_HEIGHT = 0.21,
VEG_MOISTURE  = 0.065, VEG_SV = 9770, VEG_DENSITY= 440, EMISSIVITY = 0.99,
VEG_HCONV_CYLRE = .TRUE., RGB = 110,139,61, ROUGHNESS=0.9/
&VENT XB=-150, 4,-60,60,0,0,SURF_ID='NO BURN GRASS' /
&VENT XB= 80, 150,-20,20,0,0,SURF_ID='NO BURN GRASS' /
&VENT XB= 150,210,-60,60,0,0,SURF_ID='NO BURN GRASS' /
&VENT XB= 4,150,-60,-20,0,0,SURF_ID='NO BURN GRASS' /
&VENT XB= 4,150,20,60,0,0,SURF_ID='NO BURN GRASS' /

- Ignitor fire. Delayed for 410s to allow wind to sweep through domain
&SURF
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0.125,VEG_LOAD = 0.283, VEG_HEIGHT = 0.21, VEG_MOISTURE  = 0.065, VEG_SV = 9770,
VEG_DENSITY= 440, EMISSIVITY = 0.99, VEG_HCONV_CYLRE = .TRUE. ,ROUGHNESS=0.9/
&RAMP ID='RAMPIGN',T= 0,F=0 /
&RAMP ID='RAMPIGN',T=410,F=0 /
&RAMP ID='RAMPIGN',T=412,F=1 /
&RAMP ID='RAMPIGN',T=420,F=1 /
&RAMP ID='RAMPIGN',T=422,F=0 /
&VENT XB=4,5,-20,20,0,0,SURF_ID='LINEFIRE'/

- Outputs
-- slice files
&SLCF PBY=20.0, QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBY=20.0, QUANTITY='VELOCITY'/
&SLCF PBY=20.0, QUANTITY='HRRPUV' /

&SLCF PBY=0.0, QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBY=0.0, QUANTITY='VELOCITY'/
&SLCF PBY=0.0, QUANTITY='HRRPUV' /

&SLCF PBY=-20.0, QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBY=-20.0, QUANTITY='VELOCITY'/
&SLCF PBY=-20.0, QUANTITY='HRRPUV' /

&SLCF PBZ=2.4, QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
```

&SLCF PBZ=2.4, QUANTITY='VELOCITY'/
&SLCF PBZ=1.2, QUANTITY='TEMPERATURE',VECTOR=.TRUE. /
&SLCF PBZ=1.2, QUANTITY='VELOCITY'/

-- Boundary files
&BNDF QUANTITY='WALL TEMPERATURE'/
/&BNDF QUANTITY='WALL THICKNESS'/
&BNDF QUANTITY='BURNING RATE'/
&BNDF QUANTITY='CONVECTIVE HEAT FLUX'/
&BNDF QUANTITY='RADIATIVE HEAT FLUX'/

-- Device files (gas phase point measurement)
&DEVC ID='U_0x0y2x', XYZ=0,0,2,QUANTITY='U-VELOCITY' / at x,y,z=0m,0m,2m
&DEVC ID='qr_0x0y2x',XYZ=0,0,2,QUANTITY='RADIATIVE HEAT FLUX GAS',ORIENTATION=-1,0,0 /

-- Device files -VELOCITY PROBE TREE to calculate velocity profile at various streamwise station

&DEVC XB=-25,-25,0,0,0,60, ID='VELOCITY_TREE_minus-25M', QUANTITY='U-VELOCITY',POINTS=200 / at x=-25m
&DEVC XB=-15,-15,0,0,0,60, ID='VELOCITY_TREE_minus15M', QUANTITY='U-VELOCITY',POINTS=200 / at x=-15m
&DEVC XB=-5,-5,0,0,0,60, ID='VELOCITY_TREE_minus5M', QUANTITY='U-VELOCITY',POINTS=200 / at x=-5m
&DEVC XB=2,2,0,0,0,60, ID='VELOCITY_TREE_2M', QUANTITY='U-VELOCITY',POINTS=200 / at x=2m
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&DEVC XB=20,20,0,0,0,60, ID='VELOCITY_TREE_20M', QUANTITY='U-VELOCITY',POINTS=200 / at x=20m

-- Device files -VELOCITY PROBE TREE to calculate velocity profile - in the x-direction, Z heights,

&DEVC XB=0,80,0,0,2.0,2.0, ID='Z VELOCITY_TREE_2M', QUANTITY='U-VELOCITY',POINTS=200 / at z=2.0m
&DEVC XB=0,80,0,0,6.0,6.0, ID='Z VELOCITY_TREE_6M', QUANTITY='U-VELOCITY',POINTS=200 / at z=6.0m

&DEVC XB=0,80,0,0,10.0,10.0, ID='Z VELOCITY_TREE_10M', QUANTITY='U-VELOCITY',POINTS=200 / at z=10.0m

&TAIL /
