



vegFireFOAM v1.0: a Lagrangian vegetation-fire spread module for OpenFOAM

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Abstract. Physics-based simulation of wind-driven vegetation fire requires consistent coupling among turbulent buoyant flow, gas-phase combustion, radiative and convective heating, moisture release, solid-fuel pyrolysis, char oxidation, and fuel-bed drag. Existing models mainly rely on structured Cartesian grids, extending the same coupled physics to body-fitted or unstructured terrain-resolved meshes within a modular, open-source framework remains a development need. We present vegFireFOAM v1.0, a vegetation-fire module for OpenFOAM/fireFOAM. Fuel particle is represented by Lagrangian multiphase parcels that exchange mass, species, enthalpy, momentum, and radiation with the carrier phase, using submodels for moisture release, devolatilisation, char oxidation, convective heat transfer, aerodynamic drag, and grey radiative absorption. Because the module couples through standard OpenFOAM finite-volume fields rather than a structured Cartesian mesh, the formulation can be applied to both grassland validation domains and body-fitted terrain configurations without modifying the parent solver. Fire spread therefore arises from resolved heat and mass transfer rather than from an imposed rate-of-spread closure. Evaluation uses completed, full-size simulations of two CSIRO grassland fires (C064 and F19) for quantitative validation, and a body-fitted ridge case for terrain-mesh demonstration. All three cases share the same vegetation thermochemistry and coupling options; case-specific fuel size, moisture, loading, and wind are supplied through dictionaries. For the grassland cases, least-squares fits to the filtered centerline fronts reproduce the experimental spread rates within 6.5 % for C064 and 3.9 % for F19, with coefficients of determination exceeding 0.999. The ridge calculation captures the expected slope-induced acceleration, giving a 21.2 % higher spread rate on the windward slope than on the post-crest plateau.

1 Introduction

Wildland fire behaviour is controlled by coupled processes that span fuel-element, flame, boundary-layer, and landscape scales. Wind, slope, fuel moisture, fuel geometry, turbulence, radiative and convective heat transfer, pyrolysis, char oxidation, and buoyancy influence whether heat released by the flame is transferred sufficiently far upstream to ignite unburnt fuel. Operational fire-spread systems commonly represent this complexity with empirical or semi-empirical rate-of-spread relations, often derived from Rothermel-type or related formulations and propagated over a landscape by perimeter-



growth algorithms (Rothermel, 1972; Finney, 1998; Pastor et al., 2003; Sullivan, 2009). These models are widely used in fire management because they are computationally efficient and compatible with landscape-scale fuel and weather data. For process studies, however, the spread rate is prescribed by a closure rather than obtained from resolved heat, mass, and momentum exchange between the flame, atmosphere, and fuel bed.

Physics-based wildfire simulation has developed along several complementary paths. Coupled atmosphere–fire models such as WRF-Fire/SFIRE embed a fire-spread model in a numerical weather prediction framework so that near-surface winds drive the fire while sensible and latent heat fluxes feed back to the atmosphere (Mandel et al., 2011; Kochanski et al., 2013).

This model class represents fire–atmosphere interaction, plume development, and incident-scale behavior, while combustion and fuel-bed processes at the flame front are commonly parameterized to limit computational cost. At the process scale, CFD- and LES-based models such as FIRETEC, FIRESTAR-type multiphase formulations, and WFDS/FDS resolve turbulent reacting flow and represent vegetation or porous fuel beds through thermochemical source terms (Linn et al., 2002; Morvan and Dupuy, 2004; Mell et al., 2007; McGrattan et al., 2013). These studies have examined the roles of boundary-layer turbulence, buoyancy, radiation, and fuel degradation in self-sustained spread (Sun et al., 2009). Higher physical resolution provides additional information on spread mechanisms but also increases dependence on mesh design, solver architecture, and computational resources.

OpenFOAM provides an open finite-volume framework with unstructured and body-fitted meshes, run-time model selection, source-code access, and multi-physics libraries (Weller et al., 1998). fireFOAM adds reacting-flow, turbulence, radiation, and Lagrangian-particle infrastructure for fire simulations. OpenFOAM-based fire simulations have also used adaptive mesh refinement to reduce refinement away from a propagating flame (Lapointe et al., 2021). Standard fireFOAM, however, does not include a fuel vegetation model that combines drying, pyrolysis, char oxidation, momentum exchange, radiation, and a fixed fuel-bed representation. This limits direct application to surface-fire configurations in which terrain-following grids, non-Cartesian boundaries, or extension of the coupled fuel physics are part of the modelling problem.

vegFireFOAM v1.0 adds a Lagrangian vegetation-fuel module to fireFOAM. Each computational parcel represents multiple fuel elements and contributes conservative mass, species, enthalpy, momentum, and radiation source terms to the carrier phase. The module combines moisture evaporation, volatile release, char oxidation, fuel-bed drag, grey vegetation absorption, and optional particle radiation within fireFOAM’s run-time-selectable cloud framework. Because the implementation couples through OpenFOAM finite-volume fields rather than a Cartesian fire-code mesh, the formulation can be applied to both grassland cases and body-fitted terrain configurations.

This paper describes the model equations, numerical implementation, and evaluation of vegFireFOAM v1.0. Section 2 gives the gas-phase and vegetation-phase sub-models. Section 3 summarizes the software implementation and numerical choices that materially affect reproducibility. Section 4 defines two completed full-size CSIRO grassland validation cases and a body-fitted ridge demonstration. Section 5 evaluates front propagation and resolved thermal-flow structure. Section 6 discusses limitations and appropriate use. Section 7 gives the conclusions.



2 Model description

2.1 Overview

vegFireFOAM v1.0 is built on fireFOAM, the large-eddy simulation reacting-flow solver in the FM Global fork of OpenFOAM v1912. The gas phase is treated as a compressible, low-Mach-number, turbulent reacting flow. Vegetative fuel is represented by a Lagrangian particle cloud of type basicReactingMultiphaseCloud. Each computational parcel represents a statistical sample of many geometrically identical fine-fuel elements, such as grass blades, with common diameter, density, heat capacity, and initial composition. The vegetation-specific physics is implemented in a run-time loadable library, libvegetationFireModels.so. The principal sub-models are listed in Table 1.

Table 1: Submodels for the vegFireFOAM v1.0 model

Submodel	OpenFOAM category	Role in the coupled model
vegetationLiquidEvaporation	PhaseChangeModel	applies first-order Arrhenius release of bound fuel moisture and transfers H ₂ O and reaction enthalpy to the carrier phase
vegetationRanzMarshall	HeatTransferModel	applies Ranz–Marshall convection with a fuel-area normalisation for spherical OpenFOAM parcels
VegetationDevolatilisation	DevolatilisationModel	first-order Arrhenius release of pyrolysis gas from dry fuel
VegetationCharOxidation	SurfaceReactionModel	diffusion/kinetic-limited oxidation of residual char
StaticParticleReset	CloudFunctionObject	keeps standing vegetation parcels fixed while preserving source terms
vegetationDragSource	fv::option	applies vegetation aerodynamic drag as a gas-phase volumetric momentum sink
vegetationAbsorptionEmission	radiation absorptionEmissionModel	adds grey vegetation absorption/emission to fvDOM radiation

Fire spread is modeled through two-way coupling between gas flow and vegetation combustion. The flame heats unburnt fuel by convection and radiation; the fuel releases moisture, pyrolyses, supplies combustible vapour, and leaves oxidising char. Gas-phase combustion then returns heat to the vegetation while fuel-bed drag modifies the near-surface flow. Figure 1 summarises this two-way exchange and the run-time-selectable components through which it is implemented.



vegFireFOAM v1.0: two-way gas–vegetation coupling for wildfire modeling

Eulerian fireFOAM LES coupled to static Lagrangian fine-fuel parcels

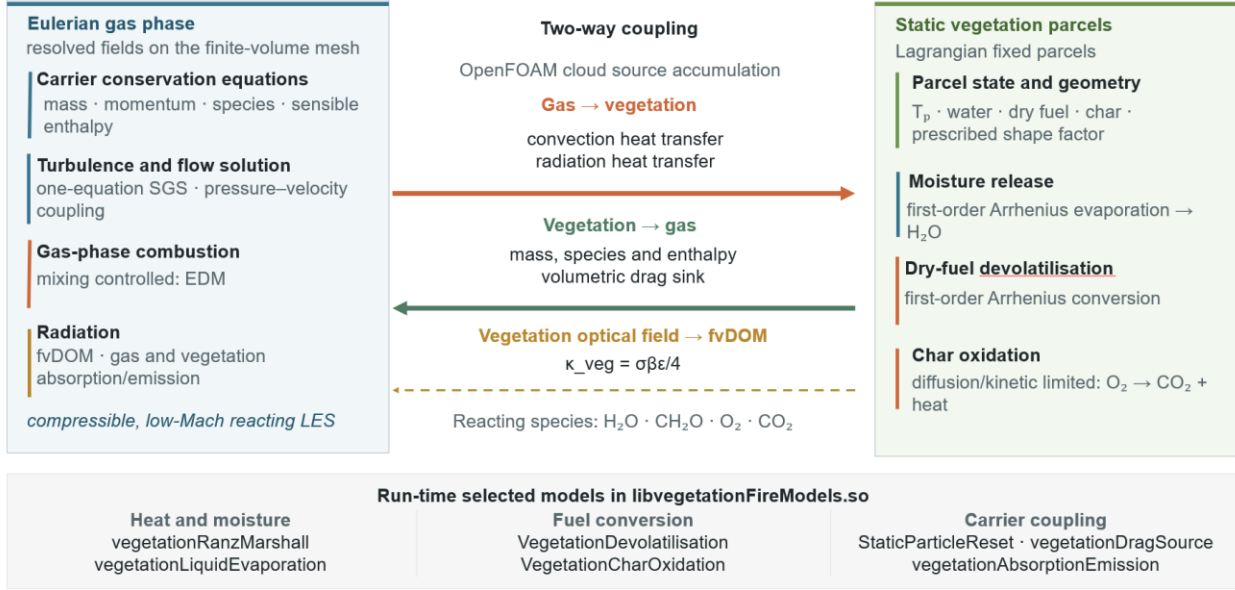


Figure 1. vegFireFOAM model. The Eulerian fireFOAM LES transfers convective heat and radiative energy to static Lagrangian vegetation parcels. Drying, devolatilisation, and char oxidation return conservative mass, species, and enthalpy sources; vegetation drag and optical properties couple momentum and fvDOM radiation. All vegetation submodels are selected at run time from libvegetationFireModels.so.

2.2 Gas-phase equations

The gas phase follows the fireFOAM formulation for low-Mach, compressible, turbulent reacting flow. Favre-filtered conservation equations are adopted:

$$\frac{\partial \bar{\rho}}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}}) = S_\rho, \quad (1)$$

$$\frac{\partial (\bar{\rho} \tilde{\mathbf{u}})}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}} \tilde{\mathbf{u}}) = -\nabla \bar{p} + \nabla \cdot (\bar{\boldsymbol{\tau}} + \boldsymbol{\tau}_{sgs}) + \bar{\rho} \mathbf{g} + \mathbf{f}_{veg}, \quad (2)$$

$$\frac{\partial (\bar{\rho} \tilde{h}_s)}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}} \tilde{h}_s) = \frac{\partial \bar{p}}{\partial t} + \nabla \cdot (\alpha_{eff} \nabla \tilde{h}_s) + \dot{Q}_c + \dot{Q}_r + S_h, \quad (3)$$

and

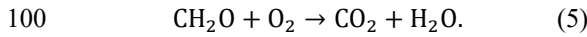
$$\frac{\partial (\bar{\rho} \tilde{Y}_i)}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{\mathbf{u}} \tilde{Y}_i) = \nabla \cdot (\bar{\rho} D_{eff} \nabla \tilde{Y}_i) + \dot{\omega}_i + S_{Y_i}, \quad i = 1, \dots, N_s. \quad (4)$$

Here $\tilde{h}_s$ is sensible enthalpy, α_{eff} and D_{eff} are effective momentum and thermal diffusivities, $\dot{\omega}_i$ denotes gas-phase chemical production of species i , and $\dot{Q}_c$ and $\dot{Q}_r$ are the combustion and radiative heat-release terms. The sub-grid stress is closed with



the turbulence model selected in the fireFOAM case dictionary; the current cases use the one-equation eddy-viscosity LES model in the FM Global v1912 build. The terms S_p , f_{veg} , S_h , and S_{Y_i} are exchange terms with the vegetation cloud.

The gas-phase combustion model is a single mixing-controlled step for the pyrolysis-gas surrogate,



The fuel heat of combustion evaluated from the thermochemical data in the case is $\Delta H_c \approx 17.5 \text{ MJ kg}^{-1}$, compared with 17.4 MJ kg^{-1} for the CSIRO/WFDS reference gas. The combustion chemistry is intentionally simple: for the present surface-fire applications the dominant requirement is to reproduce the released heat per unit mass of volatile fuel and the associated oxygen demand at LES resolution. Detailed intermediate species chemistry is outside the scope of version 1.0.

105 2.3 Lagrangian vegetation phase

Each parcel represents N_p identical fuel elements with diameter d , material density ρ_p , heat capacity c_p , and fixed geometric size. The mass of a parcel is partitioned into gas, liquid, and solid fractions in the basicReactingMultiphaseCloud composition framework,

$$m_p = m_{\text{vol}} + m_{\text{liq}} + m_{\text{sol}}, \quad (6)$$

110 where m_{vol} is the volatile fraction available for pyrolysis, m_{liq} is moisture, and m_{sol} is residual solid char/ash. The initial fractions are set from the fuel moisture content and the volatile/char split used by the reference FDS/WFDS cases. In the grass cases described here the dry-mass split is 0.75 volatile and 0.25 char. The geometric size is held fixed during thermal degradation (constantVolume true), so the particle mass changes while the representative element diameter and surface-to-volume ratio remain fixed. The present cases retain this fixed geometry; applications involving shrinkage, fragmentation, or
115 fuel-bed collapse require a geometry-dependent formulation.

Standing grass does not move during a passing surface fire. The parcels are therefore treated as static fuel elements rather than moving particles. The StaticParticleReset function object records the initial parcel positions, zeros parcel velocity after cloud motion, and restores positions if numerical tracking has displaced a parcel. The reset is applied after source-term accumulation, so evaporation, devolatilisation, surface reaction, and heat-transfer source terms are retained. Aerodynamic
120 drag is not applied as a particle force; it is instead applied directly to the gas momentum equation as a volumetric sink (Sect. 2.5). This avoids unphysical parcel acceleration and avoids the stuck-particle deletion behaviour that can occur if gravity or drag forces are left active on fixed vegetation parcels.

2.4 Particle heat transfer and thermal degradation

The parcel temperature evolves through convective heat exchange, the endothermic release of bound moisture, endothermic
125 pyrolysis, exothermic char oxidation, and optionally direct radiation to the particle. In compact form,

$$m_p c_p \frac{dT_p}{dt} = h_c A_s (T_g - T_p) + \dot{q}_{r,p} - \dot{m}_w \Delta h_w - \dot{m}_{\text{vol}} \Delta h_{\text{vol}} + \dot{m}_{\text{char}} (-\Delta h_{\text{char}}), \quad (7)$$



where A_s is the parcel surface area used by the OpenFOAM heat-transfer framework, T_g is the local gas temperature, $\dot{q}_{r,p}$ is the optional per-particle radiative source, $\dot{m}_w$ is the moisture-release rate, and Δh_w is its endothermic reaction enthalpy. In the default continuum-radiation configuration $\dot{q}_{r,p} = 0$ because the vegetation radiation source is deposited in the gas energy equation and reaches thermally thin fuel elements by gas-solid convection.

Convective heat transfer is evaluated with the vegetationRanzMarshall model,

$$\text{Nu}_{\text{eff}} = \frac{h_c d}{k_g} = F_A (2 + 0.6 \text{Re}_p^{1/2} \text{Pr}^{1/3}), \quad F_A = \frac{2}{3}. \quad (8)$$

The correction F_A reconciles the spherical area used internally by the OpenFOAM parcel class with the specified vegetation surface-to-volume ratio. For $d = 4/\sigma$, the spherical parcel has $A_s/V_p = 6/d = 1.5\sigma$; multiplying the heat-transfer coefficient by $2/3$ therefore gives an effective exchange area density of σ . This is an area normalisation of the spherical Ranz–Marshall relation, not an exact piecewise cylindrical Nusselt correlation as used by FDS. The OpenFOAM Bird correction is enabled during mass loss (Ranz and Marshall, 1952).

Bound moisture is released with the vegetationLiquidEvaporation model. The first-order rate coefficient and finite-time mass decrement are

$$k_w(T_p) = A_w T_p^{n_w} \exp\left(-\frac{E_w}{R_u T_p}\right), \quad (9)$$

$$\Delta m_w = m_w [1 - \exp(-k_w \Delta t)]. \quad (10)$$

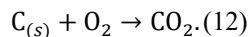
Here m_w is the bound-water mass available at the beginning of the time step. The grass cases use $A_w = 6.0 \times 10^5$, $E_w = 4.82 \times 10^7 \text{ J kmol}^{-1}$, $n_w = -0.5$, and $\Delta h_w = 2.295 \text{ MJ kg}^{-1}$; initial diameter and liquid mass fraction are supplied by each case. The released mass enters the carrier phase as H_2O , while the reaction enthalpy is removed from the parcel. The current model follows the bound-moisture kinetics as in FDS and does not add an external Sherwood-number mass-transfer resistance or direct suppression by ambient relative humidity. Ambient moisture conditions are represented through the prescribed initial fuel-moisture loading.

Dry fuel devolatilisation is represented by VegetationDevolatilisation, a first-order Arrhenius law applied to the remaining volatile mass,

$$\dot{m}_{\text{vol}} = A_v \exp\left(-\frac{E_v}{R_u T_p}\right) m_{\text{vol}}. \quad (11)$$

For the CSIRO grass cases the active model uses $A_v = 1040 \text{ s}^{-1}$ and $E_v = 6.1041 \times 10^7 \text{ J kmol}^{-1}$, corresponding to $61.041 \text{ kJ mol}^{-1}$. The released volatile species is mapped to CH_2O in the gas phase. The retained char fraction is specified through the initial solid mass fraction rather than through a kinetic char yield; in the present cases the charYield entry in the devolatilisation data is set to zero so that it does not artificially slow volatile release.

Char oxidation is handled by VegetationCharOxidation after the volatile fraction has been depleted below the residual threshold. The surface reaction consumes solid carbon and oxygen and produces CO_2 in the default configuration,





The implemented rate is the harmonic mean of a surface kinetic rate and a diffusion-limited rate,

$$\dot{m}_{\text{char}} = A_p r, \quad r = \frac{r_{\text{kin}} r_{\text{diff}}}{r_{\text{kin}} + r_{\text{diff}}}, \quad (13)$$

160 with

$$r_{\text{kin}} = A_c \exp\left(-\frac{E_c}{R_u T_p}\right) Y_{\text{O}_2}^n, \quad r_{\text{diff}} = C_1 \frac{[(T_p + T_g)/2]^{0.75}}{d}. \quad (14)$$

The rates r_{kin} and r_{diff} have units $\text{kg m}^{-2} \text{s}^{-1}$ and are evaluated using the local carrier-gas O_2 mass fraction Y_{O_2} . The reaction is limited by the available solid char and by the local oxygen mass available to the parcel during the time step. The reacting area of one fuel element is computed from the vegetation surface-to-volume ratio,

$$165 \quad A_p = \sigma V_p, \quad V_p = \frac{\pi}{6} d^3, \quad (15)$$

so that the char-oxidation area is consistent with the drag and radiation models. The active grass cases use $A_c = 4.89 \times 10^8 \text{ kg m}^{-2} \text{s}^{-1}$, $E_c = 6.8 \times 10^7 \text{ J kmol}^{-1}$, $n = 1$, $C_1 = 5.0 \times 10^{-12} \text{ kg m}^{-2} \text{s}^{-1} \text{K}^{-0.75} \text{m}$, $T_{\text{min}} = 600 \text{ K}$, and $\Delta h_{\text{char}} = -25 \text{ MJ kg}^{-1}$. The current configuration sends all oxidised carbon to CO_2 although the code supports a prescribed CO/CO_2 split when CO is included in the carrier species list.

170 2.5 Gas-vegetation coupling

2.5.1 Momentum exchange

The aerodynamic resistance of the static fuel bed is applied with `vegetationDragSource`, an `fvOption` acting on the gas velocity equation. The drag force per unit volume is

$$\mathbf{f}_{\text{veg}} = -\frac{1}{2} \rho C_d C_s a_v |\mathbf{u}| \mathbf{u}, \quad a_v = \sigma \beta, \quad (16)$$

175 where C_d is a drag coefficient, $C_s = 0.25$ is the random-orientation shape factor for cylindrical elements, a_v is the surface-area density, σ is the element surface-to-volume ratio, and $\beta = \rho_{\text{bulk}}/\rho_p$ is the packing ratio. The grass cases use $C_d = 2.8$ and $C_s = 0.25$, following the FDS/WFDS vegetation formulation. The source is linearized implicitly for numerical stability.

The model can compute a_v from a prescribed surface-area density, from $\sigma \beta$, or from the Lagrangian parcel distribution. In the current validation cases the dictionary specifies σ and β , so the fuel-bed drag is spatially uniform within the selected
 180 vegetation cell zone. If the parcel-distribution mode is used, the code sums $N_p \sigma V_p$ over parcels in each cell and divides by cell volume. Because particle geometry remains fixed during burning, this cell-wise area does not represent continuous shrinkage unless element size, parcel count, or parcel removal is also updated.

2.5.2 Mass, species, and enthalpy exchange

185 Moisture evaporation, volatile release, and char oxidation generate gas-phase mass and species source terms. Evaporation adds H_2O , devolatilisation adds CH_2O , and char oxidation consumes O_2 and adds CO_2 in the default setup. The associated enthalpy sources include latent heat of evaporation, heat of pyrolysis, and heat released by char oxidation. These cloud



source terms are accumulated over all parcels in a cell and inserted into the fireFOAM carrier equations through the Lagrangian cloud coupling already provided by basicReactingMultiphaseCloud. The total gas-phase source S_p is not externally prescribed, it is calculated by the chemical reaction from local fuel temperature and composition.

190 2.6 Thermal radiation

Radiative transfer is solved with fireFOAM's finite-volume discrete ordinates model (fvDOM) (Chui and Raithby, 1993). The radiation solution provides the incident radiation

$$G(\mathbf{x}) = \int_{4\pi} I(\mathbf{x}, \mathbf{s}) d\Omega. \quad (17)$$

The absorption-emission model is grey in the current cases and combines gas and vegetation contributions,

195
$$a = a_{\text{gas}} + \kappa_{\text{veg}}. \quad (18)$$

The gas term uses a grey-mean model whose emission includes a heat-release-rate contribution controlled by a radiant fraction, χ_r , so that unresolved flame emission is tied to chemical heat release rather than only to cell-mean gas temperature. The vegetation term follows the FDS/WFDS treatment of optically large, opaque, non-scattering vegetation elements. The vegetation absorption coefficient is the frontal-area density multiplied by emissivity,

200
$$\kappa_{\text{veg}} = C_s \sigma \beta \varepsilon = \frac{1}{4} \sigma \beta \varepsilon, \quad (19)$$

where $\varepsilon = 0.9$ in the grass cases. Scattering is neglected for the large opaque elements considered here.

The radiation emission is implemented by vegetationAbsorptionEmission, κ_{veg} is added to the continuous-phase absorption coefficient used by fvDOM. Absorbed radiation is deposited in the gas energy equation, and vegetation emission is represented implicitly through Kirchhoff's law via the absorption coefficient. The explicit emission field ECont for
205 vegetation is zero in order to avoid double-counting emission already represented by aI_b in the radiation equation and by the corresponding $4a\sigma_{\text{SB}}T^4$ term in the energy equation. Per-particle radiation is switched off in the cloud dictionary for this pathway.

2.7 Pyrolysis-gas surrogate

The CSIRO/WFDS reference cases define a custom pyrolysis gas, often labelled FUEL VAPOR, with approximate formula
210 $\text{C}_{2.10}\text{H}_{6.20}\text{O}_{2.16}$ and heat of combustion 17.4 MJ kg^{-1} (Cheney et al., 1993; Mell et al., 2007). That species is not a standard gas in the OpenFOAM thermochemical database used here. vegFireFOAM represents the volatile fuel by formaldehyde, CH_2O . Its heat of combustion in the case thermochemistry is about 17.5 MJ kg^{-1} and its stoichiometric air-fuel ratio is close to that of the reference vegetation gas. Heat release per unit mass is used as the primary surrogate-selection constraint because fire intensity and heat feedback to unburnt fuel scale with this quantity.

215 Methane is not used as the generic fuel surrogate because it releases about 50 MJ kg^{-1} , nearly three times the reference value. For a given volatile mass loss, a methane surrogate would increase heat release relative to the reference gas and consequently



bias the simulated spread rate. The CH₂O substitution is used to match the energy and stoichiometric constraints of the reference fuel vapour; it is not intended to represent detailed formaldehyde chemistry.

2.8 Atmospheric wind and ignition

220 The validation cases impose a neutral logarithmic atmospheric boundary layer at the inflow and initialise the interior with the same profile,

$$U(z) = U_{\text{ref}} \frac{\ln[(z+z_0)/z_0]}{\ln[(z_{\text{ref}}+z_0)/z_0]}, \quad (21)$$

where $z_0 = 0.03$ m and $z_{\text{ref}} = 2$ m for the CSIRO grassland cases. Initialising the interior with the same profile reduces the start-up transient that would result from imposing an ABL inlet on a uniform initial field. The ridge cases use the same
225 functional form but evaluate height above local terrain, $z - z_b(x)$, in order to initialise a terrain-following wind field.

Ignition is imposed as a temperature-limited enthalpy source (scalarCodedSource acting on h). For the moving-line grassland igniters, a cell at lateral position y is ignited at local time $t_{\text{ig}} = |y|/s$, where s is the igniter spread speed. The local source follows a trapezoidal ramp,

$$\dot{q}(y, t) = \dot{q}_{\text{peak}} f(t - t_{\text{ig}}) [[T < T_{\text{cap}}], \quad \dot{q}_{\text{peak}} = \frac{\text{HRRPUA}}{\Delta z_{\text{cell}}}. \quad (22)$$

230 The temperature cap, $T_{\text{cap}} = 1600$ K in the current cases, prevents an unphysical ignition-cell temperature overshoot and avoids contaminating temperature-based front tracking. The igniter represents the experimental procedure numerically; it is not a physical model of the ignition device. Consequently, rate-of-spread fits exclude the early acceleration and igniter-dominated period.

3 Software implementation and numerical reproducibility

235 3.1 Integration with fireFOAM

vegFireFOAM is implemented as a repository-level OpenFOAM library rather than as a fork of the fireFOAM solver. The upstream fireFoam.C and cloud-creation routines are not modified. The vegetation submodels are maintained in the shared lib/ source directory, built with ./Allwmake, and installed as libvegetationFireModels.so. A case activates the module by adding libs ("libvegetationFireModels.so"); to system/controlDict and by selecting the vegetation submodels in
240 constant/reactingCloud1Properties, constant/radiationProperties, and constant/fvOptions. The shared library is compiled once for each OpenFOAM/fireFOAM application binary interface and machine environment. Case-local copies of the same submodels are not loaded concurrently because duplicate run-time registrations would make model selection ambiguous. The build script locates the FM Global intermediateNew Lagrangian source tree, generates lnInclude if necessary, and links against the fireFOAM Lagrangian intermediate and radiation libraries. The model has been developed for OpenFOAM



245 v1912 and the FM Global fireFOAM v1912 fork; other OpenFOAM versions are outside the evaluated compatibility range until the Lagrangian and radiation APIs have been checked.

3.2 Case setup requirements

A reproducible vegetation-fire case requires the following elements:

- a basicReactingMultiphaseCloud with gas, liquid, and solid composition entries for volatile fuel, water, and char;
- 250 • vegetationRanzMarshall selected as the cloud heat-transfer model, with the documented area factor;
- vegetationLiquidEvaporation selected as the phase-change model, with case-specific initial diameter and moisture fraction;
- particleForces {} left empty for static vegetation parcels;
- StaticParticleReset enabled as a cloud function object;
- 255 • vegetationDragSource applied to the gas velocity equation over the vegetation cell zone;
- either vegetationAbsorptionEmission with cloud radiation off, or cloudAbsorptionEmission with cloud radiation on, but not both for the same vegetation absorption path;
- a gas-phase fuel species matching the devolatilisation product, here CH₂O;
- a pressure setup consistent with fireFOAM's gauge-pressure convention (p_rgh near zero with pRef carrying
- 260 atmospheric pressure); and
- an ignition source of sufficient intensity and limited duration so that the measured spread interval follows the ignition period.

Applying particle forces to static parcels can lead to repeated re-tracking and parcel deletion. Using an absolute pressure value in p_rgh while also setting pRef to atmospheric pressure introduces an artificial pressure jump. A linear solver not
265 suited to the upwind-dominated fvDOM ray equations can become the computational bottleneck or stall. The archived cases therefore include the complete 0, constant, and system directories together with the shared model library.

3.3 Post-processing and rate-of-spread extraction

Rate of spread is derived from sampled fields rather than being a primitive solver variable. The primary procedure samples a near-ground streamwise line through the head-fire centreline. At each output time, the maximum line temperature and the
270 raw downwind edge of the hot region are

$$T_{\max}(t) = \max_x T(x, t), \quad x_{\text{raw}}(t) = \max\{x: T(x, t) > 0.5T_{\max}(t)\}. \quad (23)$$

A centred temporal median filter is applied to x_{raw} , followed by a cumulative maximum,

$$x_f(t_i) = \max[x_f(t_{i-1}), \text{median}(x_{\text{raw}}(t_{i-j:i+j}))]. \quad (24)$$

The cumulative maximum suppresses false backward jumps caused by switching turbulent flame pockets and defines a non-
275 retreating post-processed spread front. It is not interpreted as instantaneous flame-tip motion. With 1 s output, the standard



grassland analysis uses $j = 3$, corresponding to a nominal seven-sample window. The strict location of maximum temperature is retained as a light-grey diagnostic because it can jump between the igniter and separate flame pockets.

For the ridge case, the same method is supplemented by two fire-detection safeguards: a front is evaluated only when $T_{\max} \geq 700$ K, and the threshold is $\max(600 \text{ K}, 0.5T_{\max})$. A five-sample median window ($j = 2$) is used. The terrain-following

280 spread coordinate is

$$s_f(t) = \int_{x_{\text{ign}}}^{x_f(t)} \sqrt{1 + \left(\frac{dz_b}{dx}\right)^2} dx. \quad (25)$$

Reported rates of spread are least-squares slopes of $s_f(t)$ over explicitly stated spatial zones. Reported fits use explicitly stated spatial or temporal intervals and include the coefficient of determination.

285 **4 Evaluation cases**

The evaluation matrix separates quantitative validation from geometric demonstration. C064 and F19 reproduce the full finite-width grass plots and are compared with independent experimental front positions. The ridge case uses the same coupled physics to test terrain-following flow, fire structure, and rate-of-spread diagnostics without claiming validation against a matched slope experiment. Figure 2 summarises the domains and boundary conditions.

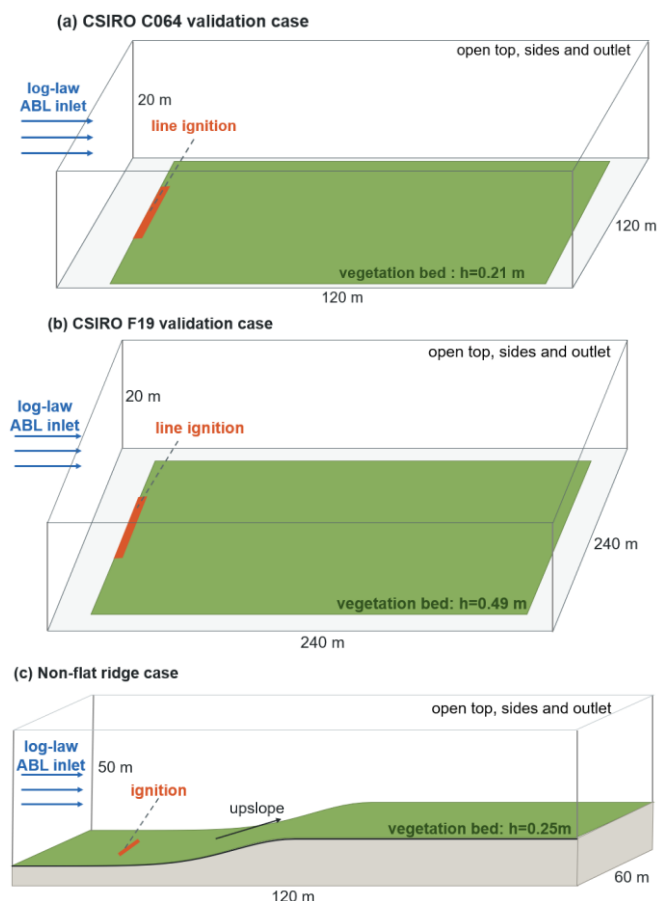


Figure 2. Computational domains and principal boundary conditions. (a) Full-size C064 domain with a 100 m by 100 m grass bed. (b) Full-size F19 domain with a 200 m by 200 m grass bed and vertically graded mesh. (c) Body-fitted ridge domain with representative terrain-following layers, the Gaussian windward slope, crest at $x=60$ m, plateau, and finite-width ignition. Blue, green, and orange denote inflow, vegetation, and ignition, respectively. Schematics are not to scale.

4.1 CSIRO C064 grassland head fire

C064 is the first quantitative validation case (Cheney et al., 1993; Mell et al., 2007). The full domain spans $x=-10$ to 110 m, $y=-60$ to 60 m, and $z=0$ to 20 m. A uniform 0.5 m mesh gives 240 by 240 by 40 cells, or 2.304 million hexahedra. The inlet and initial field use a neutral logarithmic profile with $U=4.6$ m s $^{-1}$ at $z=2$ m and roughness length $z_0=0.03$ m; the outlet, upper, and lateral boundaries allow the finite-width fire to entrain ambient air.

The 0.21 m grass bed occupies $x=0$ to 100 m and $y=-50$ to 50 m. Its 2793 kg dry mass and 6.3 % dry-basis moisture content are represented by $40\,000$ computational parcels, one in each vegetation cell of the bottom mesh layer centred at $z=0.25$ m. Each parcel represents many physical grass elements; vegetation drag is applied to the gas as a volumetric source while parcel velocity is reset to zero.



Ignition follows the reference centre-outward procedure over $x=0$ to 1.6 m and $y=-25$ to 25 m. The line advances laterally at 1 m s^{-1} ; each local segment ramps up for 1 s, remains active for 4 s, and ramps down for 1 s, so the line ends complete their pulse at approximately 31 s. A 1600 K cap prevents the igniter from controlling the temperature-based front. The analysis interval ends before the front reaches the $x=100$ m fuel edge.

310 4.2 CSIRO F19 grassland head fire

F19 provides an independent, faster-spreading grassland test from the same experimental series (Cheney et al., 1993). The domain follows the full reference extents, $x=-20$ to 220 m, $y=-120$ to 120 m, and $z=0$ to 20 m. Horizontal spacings are 0.5 m in x and 1.0 m in y ; the vertical spacing is 0.5 m below $z=4$ m and 1.0 m aloft. The resulting 480 by 240 by 24 mesh contains 2.7648 million cells while retaining 0.5 m resolution across the vegetation layer and head-fire propagation direction.

315 The 0.49 m grass bed occupies $x=0$ to 200 m and $y=-100$ to 100 m. The neutral logarithmic inflow has $U=4.8$ m s^{-1} at $z=2$ m and $z_0=0.03$ m. The base igniter covers $x=0$ to 3.3 m and $y=-87$ to 87 m and follows the 0–12 s burner schedule. Open outlet, top, and lateral boundaries permit a finite-width head and flanks to develop. All vegetation thermochemistry and coupling options are shared with C064; case-specific fuel size, moisture, loading, and wind are supplied through dictionaries rather than hard-coded model constants.

320 4.3 Body-fitted ridge demonstration

The case_ridge_slope20 calculation evaluates terrain-following mesh capability and the response of the coupled fire to slope-induced flow. The domain is 120 m by 60 m by 50 m and contains 240 by 120 by 45 cells (1.296 million body-fitted hexahedra). Horizontal spacing is 0.5 m; vertical grading gives a first-layer height of 0.248 m and approximately 3 m cells near the open upper boundary. The lateral boundaries are open so that a finite-width fire can entrain air and form flanks.

325 The terrain has a Gaussian windward face and a horizontal plateau:

$$z_b(x) = \begin{cases} H \exp \left[-\left(\frac{x-x_c}{L} \right)^2 \right], & x < x_c, \\ H, & x \geq x_c, \end{cases} \quad H = 7.5 \text{ m}, \quad x_c = 60 \text{ m}, \quad L = 18 \text{ m}. \quad (26)$$

where the ridge height is 7.5 m, the crest is at $x=60$ m, and the Gaussian length scale is 18 m, giving a maximum local slope of 19.7° . The flat background mesh is transformed vertically according to

$$z' = z + z_b(x) \cos^2 \left(\frac{\pi z}{2Z_{\text{top}}} \right), \quad Z_{\text{top}} = 50 \text{ m}. \quad (27)$$

330 so the ground conforms to the terrain while the upper boundary remains fixed. This mapping preserves the near-ground layer thickness across the slope and plateau. The grass bed spans $x=10$ to 110 m across the full 60 m width, with a wet mass of 1800 kg and areal loading of 0.30 kg m^{-2} . A stationary 12 m wide igniter occupies $x=15$ to 17 m and $y=24$ to 36 m. Ignition begins after a 30 s cold-flow spin-up and follows a 1 s rise, 14 s hold, and 1 s decay.



5 Results and evaluation

The evaluation uses three cases. C064 and F19 are full-scale grassland fires used for quantitative validation against independent experimental measurements. The ridge case demonstrates terrain-following mesh capability and slope-induced fire behaviour without claiming validation against a matched slope experiment.

For both grassland cases, the primary front is the temporally filtered, non-retreating downwind edge defined in Sect. 3.4 and sampled at $z=0.25$ m on the head-fire centreline. Reported rates are least-squares slopes over intervals that begin after initial ignition development and end before the front reaches the downwind fuel boundary. Experimental comparison is made with regressions through the plotted marker positions; these regressions provide a consistent slope diagnostic but do not remove uncertainty associated with digitisation, experimental timing, or the definition of the observed fire front.

5.1 C064 full-scale validation

The C064 front is approximately linear from 20 to 102 s (Fig. 3). The fitted OpenFOAM rate of spread is 1.096 m s^{-1} with $R^2=0.9992$. The fitted trajectory reaches the 100 m fuel edge at 102.22 s; later samples are excluded because they represent flame and plume evolution beyond the vegetation rather than continued grass-fire spread. A least-squares line through the three experimental markers gives 1.173 m s^{-1} ($R^2=0.9982$), so the model slope is lower by 0.077 m s^{-1} , or 6.5 %. The high simulated R^2 indicates that variation of the selected front diagnostic is small relative to its mean propagation over the fitting interval; it does not quantify uncertainty in the experimental marker positions or timing.

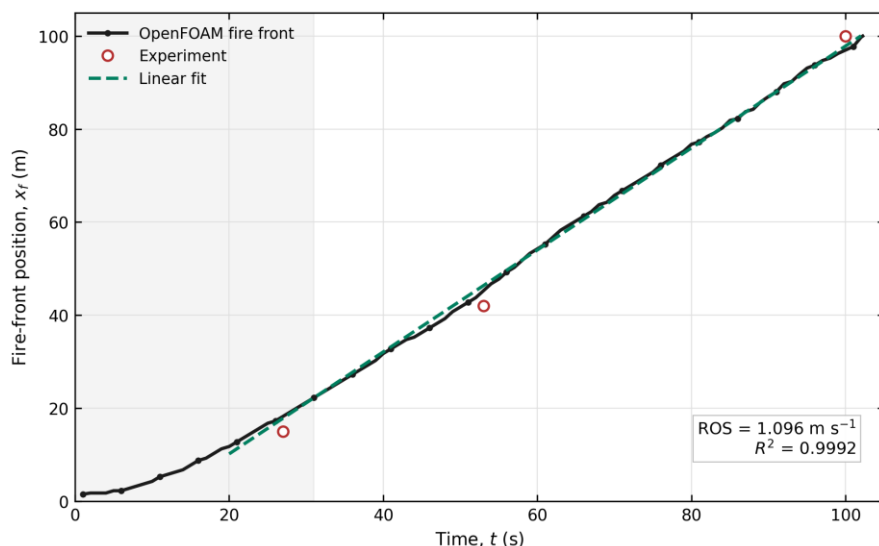


Figure 3. C064 head-fire front position. The black curve is the filtered, non-retreating OpenFOAM centreline front, the dashed green line is its least-squares fit over 20–102 s, and the open red circles are experimental markers from the CSIRO C064 record. The downwind grass-bed edge and completion of the moving ignition line delimit the interpreted spread interval.



The resolved temperature fields provide a spatial check on the front diagnostic (Fig. 4). At 40, 60, and 80 s, the detected head positions are $x=31.75$, 54.25, and 76.75 m. The front therefore advances 22.5 m in each successive 20 s interval, corresponding to 1.125 m s⁻¹ over these two windows and remaining close to the fit over the full 20–102 s interval. The near-ground fields show a laterally coherent curved head with finite flanks. Peak temperatures on the horizontal slices remain between 1334 and 1351 K, while transverse sections one metre behind the front reach 1191–1256 K. The persistence of similar temperature ranges during translation is consistent with sustained propagation after the ignition period.

The transverse sections show spatial intermittency above the fuel bed. Hot regions extend vertically and laterally within a broader preheated zone, whereas the 600 K contour remains concentrated near the active flaming region. This distribution is consistent with jumps of the instantaneous maximum-temperature location between flame pockets, even when the filtered downwind edge advances smoothly.

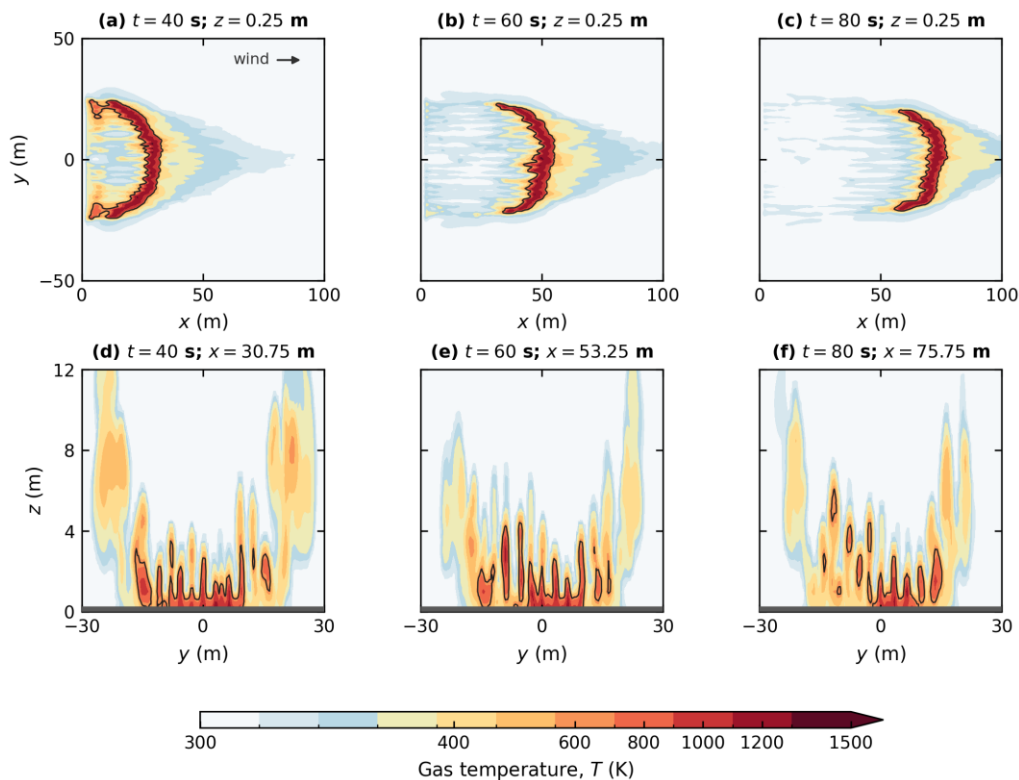


Figure 4. C064 gas-temperature evolution. (a–c) Horizontal slices at $z=0.25$ m and $t=40$, 60, and 80 s. (d–f) Transverse slices one metre behind the detected head fire at the indicated x positions and times. The black contour denotes 600 K, and the grass-bed outline is shown on the horizontal planes. The vertical coordinate in panels (d–f) is expanded by a factor of five for visibility.



5.2 F19 full-scale validation

The F19 trajectory is approximately linear over the 20–147 s interval (Fig. 5). The OpenFOAM fit gives 1.414 m s^{-1} with $R^2=0.9997$ and reaches the 200 m fuel edge at 147.36 s. Regression through the three experimental markers gives 1.472 m s^{-1} ($R^2=0.9987$), corresponding to a difference of 0.058 m s^{-1} , or a 3.9 % model underprediction. This case evaluates the

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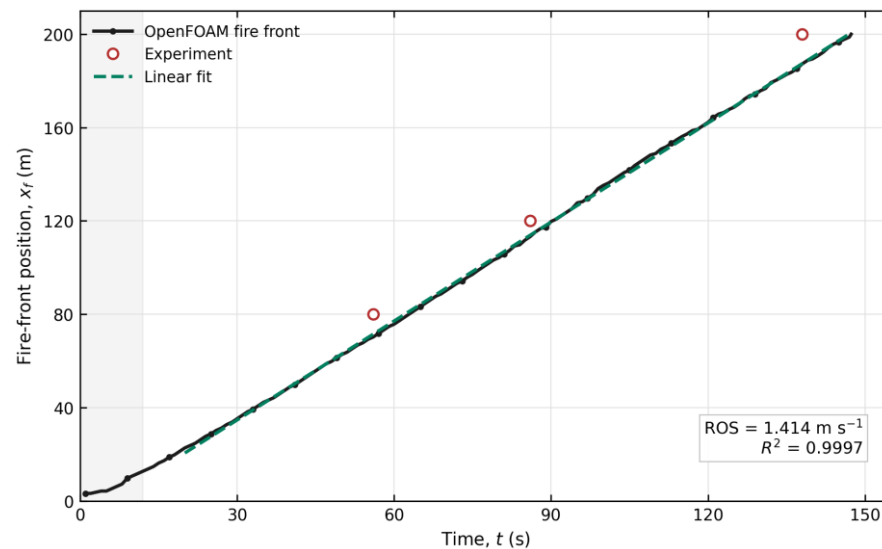


Figure 5. F19 head-fire front position. The black curve is the filtered, non-retreating OpenFOAM centreline front, the dashed green line is its least-squares fit over 20–147 s, and the open red circles are experimental markers from the CSIRO F19

380

record. Samples after the front reaches the 200 m fuel edge are excluded from the rate-of-spread fit. Near-ground temperature maps show the finite-width evolution (Fig. 6). The early field retains the broad ignition imprint, after which a downwind head and trailing flanks develop and propagate across the 200 m grass bed. From 20 to 135 s, slice maxima remain within 1374–1487 K while the active front translates downstream. At 154 s the front is beyond the fitting boundary and the slice maximum reaches 1870 K. This final maximum is excluded from the grass-spread measurement

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because the source region and plume geometry have changed beyond the fuel edge. The finite-width configuration also represents lateral entrainment and the development of head and flank regions, which are absent from a quasi-two-dimensional strip. The centreline diagnostic follows the fastest downwind path through this three-dimensional structure and therefore characterises head-fire propagation; it does not quantify lateral spread or flank rate.

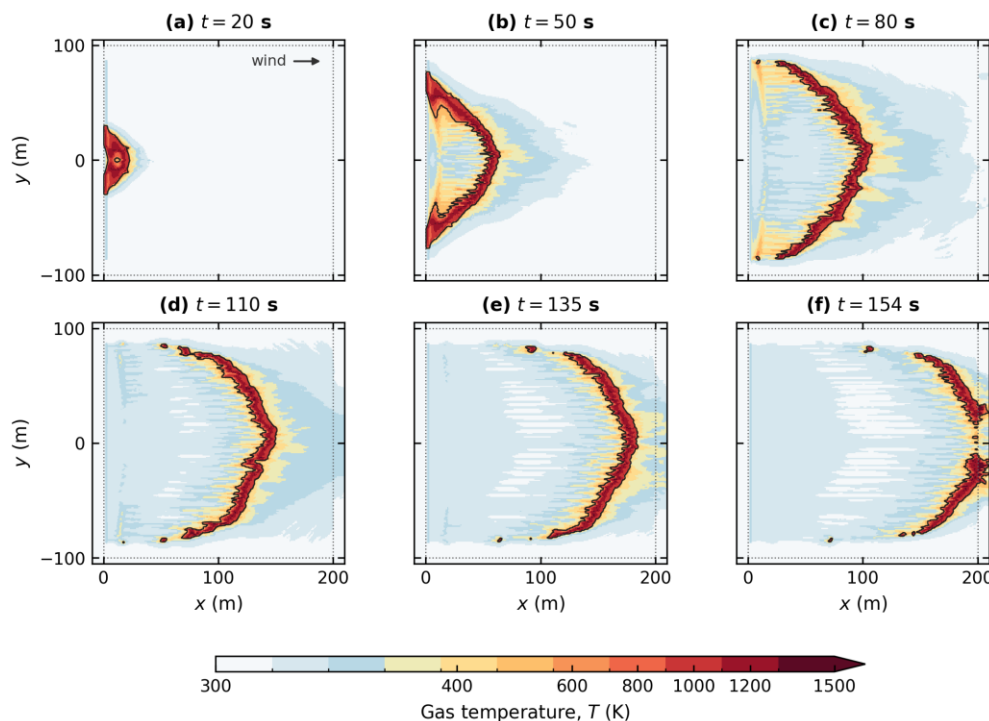


Figure 6. F19 near-ground gas temperature at $z=0.25$ m and $t=20, 50, 80, 110, 135$, and 154 s. The sequence shows development of the finite-width head and flanks across the 200 m grass bed. The 154 s field is after the centreline front has reached the downwind fuel edge and is shown only to document the post-edge thermal state.

5.3 Body-fitted ridge demonstration

Figure 7 shows the centre-plane body-fitted mesh over the full ridge domain. The terrain-following layers remain smooth through the windward transition and onto the plateau, and the near-ground spacing is retained along the surface. The first-layer height is 0.248 m; consequently, the represented fuel-layer thickness remains constant across the mapped terrain.

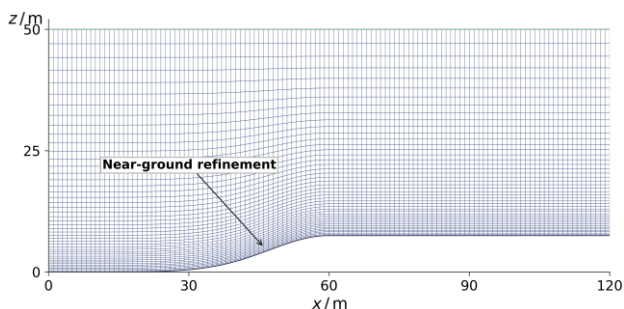




Figure 7. Centre-plane body-fitted ridge mesh over the 120 m domain. Terrain-following layers conform to the Gaussian
400 windward slope and plateau, and the first near-ground layer is 0.248 m high. The three-dimensional mesh contains 1.296
million hexahedral cells.

At $t=62$ s, or 32 s after ignition, the 450 K isosurface forms a finite-width three-dimensional region above the windward fuel
bed (Fig. 8). The isosurface is concentrated near the established head-fire region and follows the local terrain orientation.
405 This calculation evaluates propagation on the body-fitted mesh without a separate empirical slope multiplier; the isosurface
alone is not used as a quantitative validation of flame temperature or slope response.

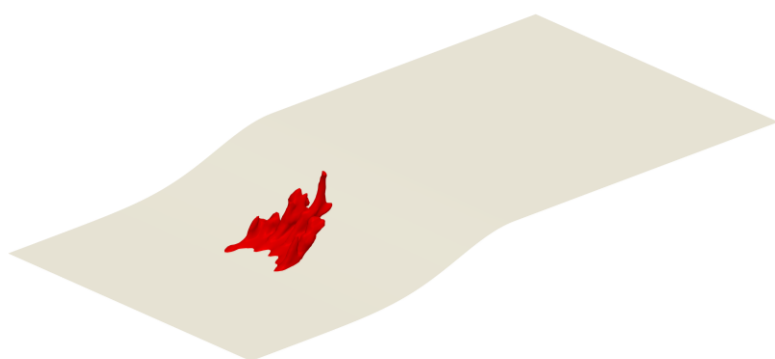


Figure 8. Gas-temperature isosurface at $T=450$ K over the body-fitted ridge at $t=62$ s (32 s after ignition). The red surface
denotes the selected temperature isosurface, and the beige surface denotes the terrain.

410 The centre-plane fields at the same instant relate the thermal region to the local flow (Fig. 9). The interpolated section
reaches 1209.6 K and a maximum velocity magnitude of 8.85 m s^{-1} . The velocity colour scale is limited to 7 m s^{-1} , so
larger values appear saturated in panel (b). Velocity vectors turn upward over the windward surface and accelerate toward
the crest, while the high-temperature region remains close to the fuel before extending into the plume. The combined fields
415 show terrain-parallel near-surface advection beneath upward plume motion, both of which contribute to heat transport ahead
of the front.

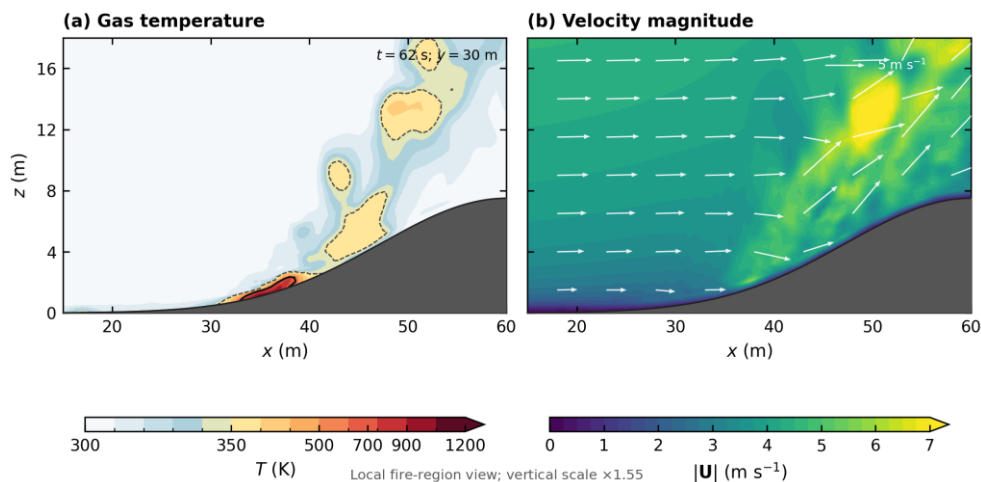


Figure 9. Centre-plane ridge fields at $y=30$ m and $t=62$ s. (a) Gas temperature with 350 and 600 K contours. (b) Velocity magnitude with in-plane velocity vectors. Both panels use common physical limits; the displayed vertical coordinate is expanded by a factor of 1.55 to reveal the near-surface structure.

Zone-wise fits quantify the accompanying change in propagation (Fig. 10). The 17–24 m segment gives 0.496 m s^{-1} ($R^2=0.972$), but this approximately 6 m interval immediately follows ignition and is treated as an acceleration transient rather than a flat-ground reference. The windward-slope fit is 1.027 m s^{-1} ($R^2=0.984$), whereas the post-crest plateau fit is 0.848 m s^{-1} ($R^2=0.995$). The windward value is 21.2 % larger than the plateau value. Both later intervals contain a developed fire, but the plateau retains upstream flow and flame history and is therefore interpreted as a post-crest result rather than an independent flat-terrain control.

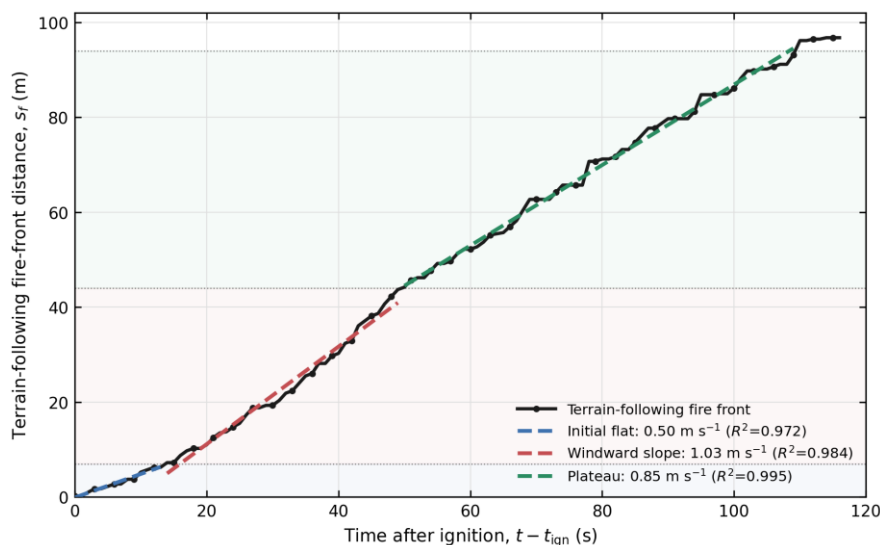




Figure 10. Terrain-following ridge fire-front distance versus time after ignition. Dashed lines are least-squares fits over the
430 ignition-transient flat segment, windward slope, and post-crest plateau. Horizontal dotted lines mark the corresponding
spatial-zone transitions. The initial segment is reported as a transient and is not used as an intrinsic flat-terrain baseline.

Figures 7–10 show the tested terrain functionality: the body-fitted mesh represents slope-modified flow, the flame remains
three-dimensional, and the terrain-following diagnostic changes between the windward and post-crest zones without an
435 empirical slope multiplier. Because only one terrain shape, inflow, fuel bed, and grid are considered, the ridge results
constitute a numerical demonstration rather than validation of slope-fire prediction.

6 Discussion

vegFireFOAM v1.0 is intended for resolved or partially resolved fine-fuel surface fires in laboratory, field-scale, and terrain-
440 resolved domains. The OpenFOAM/fireFOAM implementation provides conservative finite-volume coupling, body-fitted
and unstructured meshes, parallel decomposition, and run-time-selectable physics. The present evaluation is limited to wind-
driven grass fires and a single ridge configuration; its applicability to operational forecasting or other fuel and atmospheric
regimes remains to be established.

445 The present scope excludes crown-fire transition, spotting, firebrand transport, dynamic fuel-bed collapse, suppression, and
coupled mesoscale atmospheric feedbacks. Gas-phase chemistry is represented by one global reaction, radiation is grey, and
unresolved flame emission uses a prescribed radiant fraction. Applications in which these processes dominate require
additional submodels and case-specific validation rather than extrapolation from the present grassland tests.

450 The current Lagrangian fuel elements lose mass but retain their representative diameter and surface-to-volume ratio. This
sub-grid simplification keeps convective area, drag area, and radiation absorption area fixed unless the parcel distribution
changes. Aerodynamic and radiative blockage can therefore remain in a cell after most fuel mass has been consumed. In the
present grass cases, interpretation focuses on the leading spread rate rather than post-burn flow through the residual fuel bed.
A later geometric-area relation based on remaining dry mass, or a burnout threshold that removes aerodynamic and radiative
455 contributions, would address this limitation.

Several uncertainties affect the grassland comparisons: the measured wind is not a perfectly steady logarithmic inflow, fuel
loading and moisture vary spatially, the numerical ignition procedure approximates the field ignition, and the observed and
simulated fronts use different diagnostics. Relative to regressions through the markers plotted here, C064 and F19 are
460 underpredicted by 6.5 % and 3.9 %, respectively.



7 Conclusions

vegFireFOAM v1.0 adds a vegetation-fire coupling module to fireFOAM while retaining the parent reacting-flow solver architecture. Fine fuel is represented by Lagrangian parcels that exchange moisture, volatiles, enthalpy, momentum, and radiation with the carrier phase. Fire spread emerges from the resolved heat, mass, and momentum exchange between the flame, atmosphere, and fuel bed. The same formulation applies to both flat grassland domains and body-fitted terrain meshes.

Completed full-size C064 and F19 simulations give centreline rates of spread of 1.096 and 1.414 m s⁻¹. These slopes are 6.5% and 3.9% below regressions through the experimental markers plotted in this study. The resolved temperature sequences show finite-width heads and flanks over the fitting intervals. Within the selected front definition and fitting windows, the spatial fields are consistent with propagation after the ignition period and before the downwind fuel boundary is reached. The ridge calculation applies the same coupling formulation to a terrain with 7.5 m relief and a 19.7° maximum slope, represented with a 0.248 m first body-fitted layer. The terrain-following rate is 1.027 m s⁻¹ on the windward face and 0.848 m s⁻¹ on the post-crest plateau, a 21.2 % difference accompanied by slope-aligned flow acceleration.

The current model scope includes fixed fuel-element geometry, single-step gas chemistry, grey radiation, prescribed unresolved flame emission, moisture kinetics without external mass-transfer resistance, and no dynamic fuel motion or spotting. The present evaluation does not include grid and parameter sensitivity, matched slope-fire measurements, additional fuel classes, shrinking or fragmenting fuel geometry, or non-grey and directly coupled particle radiation. These limitations create needs for further evaluation of terrain-resolved vegetation-fire applications.

Code, data, or code and data availability

The OpenFOAM (version 1912) software, modified fireFOAM solver, the vegetationFireModel, three cases and OpenFOAM configurations are available at Zenodo: <https://doi.org/10.5281/zenodo.21885211>. (Sun 2026)

Author contributions

YJS developed the model code, YJS performed the simulations, YJS and LJ analysed the results and prepared the figures, YJS prepared the manuscript with contributions from all co-authors.



Competing interests

There are no potential conflicts of interest.

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495 References

- Cheney, N. P., Gould, J. S., and Catchpole, W. R.: The influence of fuel, weather and fire shape variables on fire-spread in grasslands, *Int. J. Wildland Fire*, 3, 31–44, <https://doi.org/10.1071/WF9930031>, 1993.
- Chui, E. H. and Raithby, G. D.: Computation of radiant heat transfer on a nonorthogonal mesh using the finite-volume method, *Numer. Heat Tr. B-Fund.*, 23, 269–288, <https://doi.org/10.1080/10407799308914901>, 1993.
- 500 Finney, M. A.: FARSITE: Fire Area Simulator—model development and evaluation, Research Paper RMRS-RP-4, USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, 47 pp., <https://doi.org/10.2737/RMRS-RP-4>, 1998.
- Kochanski, A. K., Jenkins, M. A., Krueger, S. K., Mandel, J., and Beezley, J. D.: Real time simulation of 2007 Santa Ana fires, *Forest Ecol. Manag.*, 294, 136–149, <https://doi.org/10.1016/j.foreco.2012.12.014>, 2013.
- Lapointe, C., Wimer, N. T., Glusman, J. F., Sardana, P., Makowiecki, A. S., Daily, J. W., Rieker, G. B., and Hamlington, P.
- 505 E.: Efficient simulations of propagating flames using adaptive mesh refinement, *arXiv [preprint]*, <https://doi.org/10.48550/arXiv.2102.09349>, 2021.
- Linn, R., Reisner, J., Colman, J. J., and Winterkamp, J.: Studying wildfire behavior using FIRETEC, *Int. J. Wildland Fire*, 11, 233–246, <https://doi.org/10.1071/WF02007>, 2002.
- Mandel, J., Beezley, J. D., and Kochanski, A. K.: Coupled atmosphere–wildland fire modeling with WRF 3.3 and SFIRE
- 510 2011, *Geosci. Model Dev.*, 4, 591–610, <https://doi.org/10.5194/gmd-4-591-2011>, 2011.
- McGrattan, K. B., Hostikka, S., McDermott, R. J., Floyd, J. E., Weinschenk, C. G., and Overholt, K.: Fire Dynamics Simulator Technical Reference Guide, Volume 1: Mathematical Model, 6th edn., NIST SP 1018e6, National Institute of Standards and Technology, Gaithersburg, MD, <https://doi.org/10.6028/NIST.SP.1018e6>, 2013.
- Mell, W., Jenkins, M. A., Gould, J., and Cheney, P.: A physics-based approach to modelling grassland fires, *Int. J. Wildland*
- 515 *Fire*, 16, 1–22, <https://doi.org/10.1071/WF06002>, 2007.



- Morvan, D. and Dupuy, J.-L.: Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation, *Combust. Flame*, 138, 199–210, <https://doi.org/10.1016/j.combustflame.2004.05.001>, 2004.
- Pastor, E., Zárate, L., Planas, E., and Arnaldos, J.: Mathematical models and calculation systems for the study of wildland fire behaviour, *Prog. Energ. Combust.*, 29, 139–153, [https://doi.org/10.1016/S0360-1285\(03\)00017-0](https://doi.org/10.1016/S0360-1285(03)00017-0), 2003.
- 520 Ranz, W. E. and Marshall, W. R.: Evaporation from drops, Parts I and II, *Chem. Eng. Prog.*, 48, 141–146 and 173–180, 1952.
- Rothermel, R. C.: A mathematical model for predicting fire spread in wildland fuels, Research Paper INT-115, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 40 pp., <https://research.fs.usda.gov/treesearch/32533>, 1972.
- Sullivan, A. L.: Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models, *Int. J. Wildland*
- 525 *Fire*, 18, 349–368, <https://doi.org/10.1071/WF06143>, 2009.
- Sun, R., Krueger, S. K., Jenkins, M. A., Zulauf, M. A., and Charney, J. J.: The importance of fire–atmosphere coupling and boundary-layer turbulence to wildfire spread, *Int. J. Wildland Fire*, 18, 50–60, <https://doi.org/10.1071/WF07072>, 2009.
- Sun, Y.: vegFireFOAM v1.0: a Lagrangian vegetation-fire spread module for OpenFOAM: code and data, Zenodo, <https://doi.org/10.5281/zenodo.21885211>.
- 530 Weller, H. G., Tabor, G., Jasak, H., and Fureby, C.: A tensorial approach to computational continuum mechanics using object-oriented techniques, *Comput. Phys.*, 12, 620–631, <https://doi.org/10.1063/1.168744>, 1998.