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Three fuel models for predicting urban fire spread – a stopgap for emergency management in the US

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ABSTRACT

Background. Prevailing American wildland fire modelling systems fail to predict fire growth in urban areas due to the absence of burnable urban fuels. **Aims.** This research aims to identify fuel models that optimise fire spread in urban areas relative to a hypothetical fire spread model derived from observations of recent urban fires. **Methods.** A target Rate of Spread (RoS) is derived from observations of seven urban conflagrations to anchor the model to absolute RoS. Exhaustive parameter sweeps are used to identify combinations of fuel variables that result in optimal performance. **Key results.** The target RoS is 0.81 km/h. Parameter sweeps converge on unique sets of fuel parameters including (1) BU0, an unconstrained custom fuel model; (2) BU1, a custom fuel model that operates within the constraints of current US modelling systems; and (3) Anderson Fuel Model 9, a best-performing standard fuel model. **Conclusions & implications.** Although this approach stretches current modelling systems beyond their intended design, the resultant fuel models provide a necessary stopgap for emergency management until urban-specific fire spread models find their way into operational use.

Keywords: conflagration, emergency management, fire behaviour fuel model, fire behaviour modelling, fire modelling system, Rate of Spread, Rothermel, United States, urban fire.

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Introduction

The entrenched Rothermel-based fire modelling systems supporting US wildland fire management treat the urban environment as non-burnable, a barrier to fire spread (Rothermel 1972; Finney 2006; Mell *et al.* 2011; Noonan-Wright *et al.* 2011; Drury *et al.* 2016; Andrews 2018). Fuel that can contribute to wildfire spread is a complex spectrum, but a practical definition of these urban areas follows the fire behaviour fuel model (FBFM) description for non-burnable model 91, Urban/Developed, being 'must not support wildland fire spread…structure ignition…is either house-to-house or by firebrands, neither of which is directly modeled…' (Scott and Burgan 2005). An immediate need exists to incorporate this urban fire spread in these modelling systems because urban conflagrations are becoming more common and destructive (Balch *et al.* 2024) and wildland resources can be tasked with planning for and managing them. Modellers are already incorporating approaches that leverage the Rothermel model despite scientific misgivings, as the current wildfire crisis demands timely operational predictions and risk assessments.

The geospatial systems that utilise the Rothermel spread equations include FlamMap (Finney 2006), FARSITE (Finney 2004), FSIM (Finney *et al.* 2011*a*), FSPRO (Finney *et al.* 2011*b*), WFDSS (Noonan-Wright *et al.* 2011), CAWFE (Coen 2013), WRF-SFIRE (Coen *et al.* 2013), ELMFIRE (Lautenberger 2013), ForeFire (Filippi 2018), and Pyrecast (Pyrecast 2024). Several applications of these models incorporate urban spread to represent previous wildfires (e.g. Kochanski *et al.* 2013; Shamsaei *et al.* 2023) with Juliano *et al.* (2023) concluding that consideration of urban fuels is necessary for reliable prediction. New models coupling wildland spread with urban spread have been suggested or are being developed, such as a mathematical model of wind entrainment from burning structures (Rhem 2008; Rhem and Mell 2009) and an urban spread module for the ELMFIRE model (Purnomo *et al.* 2024), among others (Mahmoud and Chulahwat 2018; Masoudvaziri *et al.* 2021). A post-simulation approach is to interpolate burn probability estimates into adjacent urban areas for community-scale risk assessment (Scott *et al.* 2020).

Fuel model substitution is a common and straightforward stopgap for existing systems, although these can have faster fire spread relative to adjacent wildlands or not represent rates of spread, which may then distort estimates of fire risk (Kearns *et al.* 2022; California Forest Observatory 2024; Natural Climate Solutions Data Atlas 2024). Alternatively, modification of individual fuel parameters, termed 'custom fuel models', to achieve desired fire behaviour has long been supported (Wu *et al.* 2011; Parresol *et al.* 2012; Cai *et al.* 2014; Elia *et al.* 2015). Lastly, direct modification of Rate of Spread (RoS) through simple adjustment factors is available (Finney 2006; Finney *et al.* 2011*b*).

Here, we press beyond the intended designs of the Rothermel-based modelling systems by systematically modifying fuel parameters without regard for vegetative realism to identify FBFMs for use in predicting urban fire spread across a range of wind and moisture conditions. Objectives are twofold: (1) derive an urban-specific fire RoS target and a logical RoS response to wind and fuel moisture variation from fire observations and model predictions, and (2) identify best-performing FBFMs for urban fire spread using comprehensive parameter sweeps of fuel inputs. The result is a set of three FBFMs useful for simulating fire spread in urban conflagrations – a stopgap until model development catches up to the needs of the current wildfire crisis.

Methods

Weather–urban fire spread relationship

A simple hypothetical relationship of wind and fuel moisture to urban fire spread informs FBFM development (Fig. 1, upper left). We assume a threshold to active fire spread that is greater than wildland fuel complexes and once exceeded, increases linearly as a function of wind speed. The Rothermel spread model generally produces slightly to moderately curvilinear relationships with wind speed, dependent on wildland fuel parameters (Anderson 1982; Scott and Burgan 2005). For extensive background, equations, and references, readers should refer to Andrews (2018).

Threshold behaviour is difficult to model, and the expected response of fire spread to changing environmental conditions in urban environments was beyond model design in initial trials. However, a curvilinear response shape with increased slope near a boundary can serve as a fuzzy threshold. To find fire spread observations that can, at a minimum, anchor this relationship to absolute RoS values, we utilised a recent dataset of community-scale wildfire spread (Rhem *et al.* 2002) observations (Szasdi-Bardales 2019; Masoudvaziri *et al.* 2021). These observations were taken from the portions of wildland fires that ignited urban areas where spatial progression information was available (Fig. 2). The RoS was estimated using the normal vectors between progression contours. The range of observational time periods was 1–9 h within a single burn period.

Notably, no correlation was observed between the empirical dataset's reported wind speed, which was taken from nearby weather station data, and fire spread rate (Spearman's $\rho = -0.11$). This is likely due to variable and complex wildland and urban fuel patterns, time delay between fire arrival and observation, and poor representation of local winds from the weather station data (Coen *et al.* 2018; Fovell and Gallagher 2018). However, these data represent observations of recent fires in dry, windy conditions that overwhelmed suppression resources and incurred most of the urban loss within a single burn period – an emerging set of commonalities documented in other destructive wildfires (Cruz *et al.* 2020; Calkin *et al.* 2023; Balch *et al.* 2024). The wind response is limited to the constraints of the Rothermel model, in any case, and therefore, we relied on the simplest model by averaging observations of fire spread to arrive at a mean 0.81 km/h RoS. We then treat this as a representation of the tail (but not an assumed maximum) of the expected range of the urban RoS distribution (hereafter the 'RoS target'), which may be the only portion that is expressed given heavy fire suppression (Kreider *et al.* 2024). This RoS target informs the optimisation of fuel parameters described below.

Fire behaviour fuel model parameter sweeps

The ability of the Rothermel systems to represent a non-linear RoS-wind response was assessed through a series of parameter sweeps modifying the fuel, wind, and moisture inputs (Table 1). For each unique combination of fuel and weather parameters, RoS was estimated using the 'firebehavior' R package (v. 0.1.2) (Ziegler *et al.* 2019), which produces the same predictions as other related systems, such as Nexus (v. 2.1) (Scott 1999), except for not implementing the effective wind limit, which caps the maximum RoS when the ratio of wind speed (ft/min) to the reaction intensity (btu/ft^2 min) exceeds 0.9 (Andrews 2018).

The first parameter sweep tested more than 200 million unique combinations of model inputs informed by the ranges of values of existing FBFMs (Scott and Burgan 2005) with a ballooning, exhaustive parameter search grid (Table 1). Not every parameter was evaluated through its entire range to reduce combinations that added unnecessary computational burden. For example, the moisture of extinction was fixed at 12%, matching the lowest extinction moisture in the standard FBFMs, under the assumption that community-scale wildfires only occur in dry conditions.

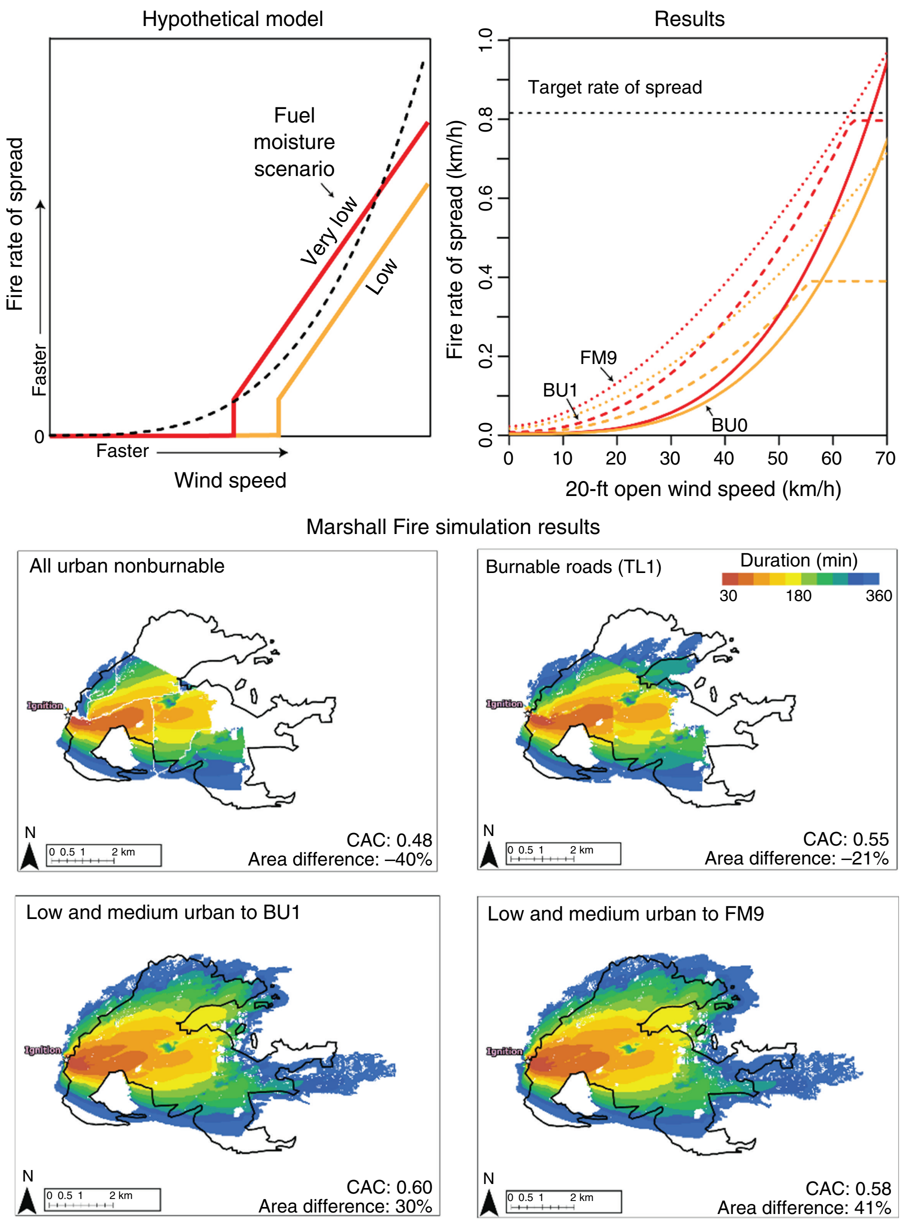

Fig. 1. (Upper left) Hypothetical relationship of fire Rate of Spread (RoS) and wind speed in urban conflagrations. Solid lines depict linear relationships after threshold wind speed and fuel moisture conditions are exceeded. The dashed black line shows how a curvilinear relationship can serve as a proxy for a discrete threshold without explicit threshold delineation; (Upper right) Predicted RoS in very low (red) and low (orange) fuel moisture scenarios for the three fire behaviour fuel models resulting from parameter sweeps. BU0 (solid lines) is the best-performing set of parameters but is not implementable in current spatial fire models. BU1 (dashed lines) is fully implementable with the effective wind limit, which caps maximum spread rate. Anderson Fuel Model 9 (FM9, dotted lines) is the best performing standard model; (Bottom group of four) Example simulation results (FlamMap MTT 6.2) of the 2021 Marshall Fire depicting fire progression (colours) using traditional unburnable urban fuels (upper left), a common approach of converting roads to a slow-spreading fuel model (upper right), low/moderate intensity urban areas plus roads set to BU1 (bottom left), and low/moderate intensity urban set to FM9 (bottom right). The black polygon is the observed fire perimeter. Other model parameters include the standard LANDFIRE (2020) fuel models, a very low fuel moisture scenario, constant 48.3 km/h wind speed at 260° wind direction, and a 6 h simulation duration. CAC is the coefficient of areal correspondence (area of intersection divided by area of union; Kimerling *et al.* 2012) and Area difference is the difference in burned area between simulated and observed.

The next two sweeps were implemented through a semi-supervised iterative process that first searched the available parameter spaces defined in Table 1 at broad parameter intervals that initially mirrored those in the first sweep. In successive iterations, the range was redefined and narrowed allowing for finer intervals, defined as quantiles of the remaining range, allowing for computational efficiency while still evaluating all relevant parameter combinations. Successive iterations continued until the parameter sets converged on optimal values using the 'paramtest' R package (v. 0.1.0) (Hughes 2017).

The second sweep targeted desired spread characteristics regardless of allowable parameter value ranges in existing fire modelling systems. Optimal parameters were defined as those that maximised the non-linear response to wind to adhere to the hypothetical model (Fig. 1) while also remaining within 10% of the RoS target (0.81 km/h) at ≥60 km/h open wind speed (US convention of 20 ft). The previously derived 0.81 km/h RoS target was set as the near-maximum target under the 'very low' fuel moisture scenario (Table 1). The resultant custom fuel model is called BU0.

The third parameter sweep was intended for implementation and sought to replicate the results of the second sweep but under the constraints of the allowable parameter ranges and the effective wind limit in the current iterations of the fire modelling systems. Therefore, we maximised the allowable surface area to volume (SAV) ratios and removed the 10 and 100-h fuel parameters because the corresponding SAV ratios cannot be modified in custom fuel input files. The effective wind limit offered the benefit of allowing the parameter sweep to converge on optimal parameters while

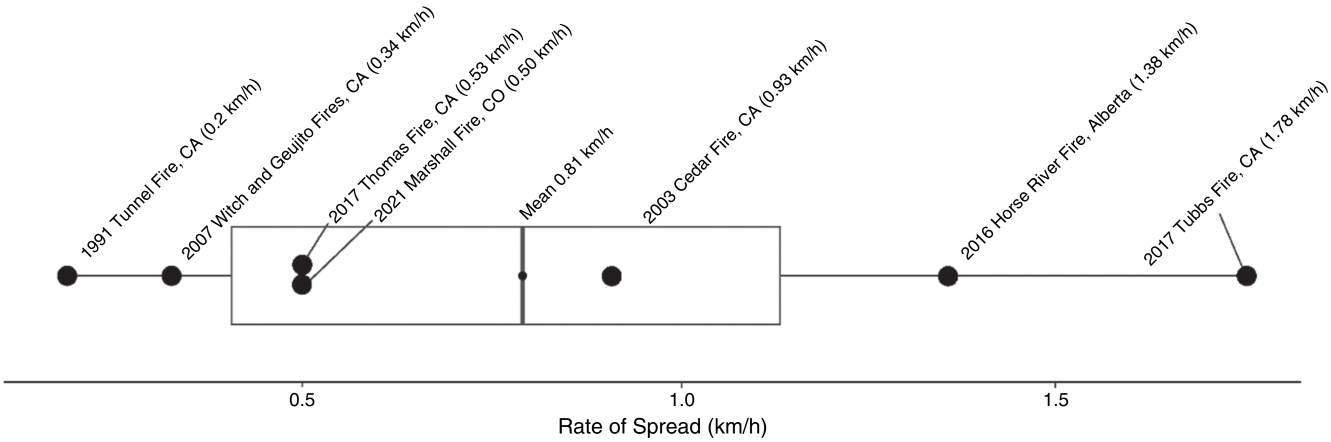

Fig. 2. Boxplot of Rate of Spread (RoS) fire observations taken from the urban portions of community-scale wildfires (Szasdi-Bardales 2019; Masoudvaziri *et al.* 2021). The mean (0.81 km/h) was used as the fire RoS target value to anchor model response to an absolute RoS.

not explicitly defining a corresponding wind speed for the RoS target, which was not definable from available empirical datasets (Szasdi-Bardales 2019; Cruz *et al.* 2020; Masoudvaziri *et al.* 2021). Therefore, the third parameter sweep was set up to identify parameters that provided a non-linear response as a function of wind speed by first maximising the allowable SAV ratio and second, invoking an effective wind limit that caused a maximum mean RoS of 0.81 km/h RoS in the driest scenario. The resultant custom fuel model which operates within the constraints of current US modelling systems is called BU1.

Finally, we considered modelling systems that do not allow for customisation of fuel model inputs, especially the Wildland Fire Decision Support System (Noonan-Wright *et al.* 2011), which restricts users to the two established wildland FBFM collections (Anderson 1982; Scott and Burgan 2005). We searched for the best match of an existing FBFM by minimising root-mean-squared-error and bias metrics using the 'bestFM' function in the 'Rothermel' R package (v. 1.2) (Vacchiano and Ascoli 2014; Ascoli *et al.* 2015). The function quantifies differences among RoS predictions from each FBFM to an observation dataset. The set of 'observations' provided to the function were the predicted values from the custom FBFM derived in the second parameter sweep, which was considered the best-available representation of urban spread.

Results and discussion

The first parameter sweep found expansive predictive space capable of almost any RoS. Indeed, the ability to generate virtually any RoS means the onus is on the modeller and consumers to scrutinise outputs, especially when utilising anything outside of the standard set of fuel models. The 99th percentile RoS ranged from 0.25 km/h with no wind to 70.2 km/h RoS at 80 km/h open wind speed. The majority of RoS response shapes to wind were linear; however, at high characteristic SAV ratios (>7333 m^{-1}) the response was curvilinear due to increased sensitivity to wind speed.

The second parameter sweep converged on a custom FBFM (BU0) with a light total fuel load (1.6 Mg/ha), unnaturally high 1-h SAV ratio (30,000 m^{-1}), and a shallow (1.5 cm) fuel bed depth (Table 1). The high characteristic SAV ratio created the non-linear response to wind, reaching the target RoS (0.81 km/h) at 66 km/h open wind speed in the very low fuel moisture scenario (Fig. 1, upper right). However, the low reaction intensity causes the effective wind limit to cap the RoS at 0.01 km/h at all wind speeds. The SAV ratio also exceeds the current systems' allowable range for custom inputs. Therefore, BU0 is not implementable in existing US systems. Given this, the extreme 1-h SAV ratio, and the dependence of SAV for several intermediate calculations, any use of BU0 should warrant additional scrutiny of outputs and is generally considered useful only for specific situations, such as in this study where the BU0 predictions were used to find the best-available standard fuel model.

The third parameter sweep found that higher 1-h (6.54 Mg/ha) and live woody (27.0 Mg/ha) fuel loads and a deeper fuel bed depth (20 cm) at the maximum allowable SAV ratio of 13,120 m^{-1} (Table 1) produced a curvilinear response that was capped by the effective wind limit at 0.8 km/h in the very low fuel moisture scenario. The added fuel loading and depth generated additional reaction intensity causing faster than desired rates of spread at lower winds (BU1; Fig. 1, upper right). These results highlight the balance needed to achieve a high sensitivity to wind while reducing reaction intensity at low wind speeds to avoid excessive RoS. However, the reaction intensity cannot be so low as to trigger the effective wind limit that immediately caps the RoS response.

The stronger fire reaction intensity in BU1 relative to BU0 delayed the wind limit RoS threshold until the open wind speed reached 64 km/h, with a maximum spread rate of 0.80 km/h in the very low fuel moisture scenario. For the 'low' fuel moisture scenario, the wind limit is 56 km/h with

Table 1. Burnable urban fire behaviour fuel model (FBFM) parameters and a description of the parameter sweeps to derive the FBFMs.

Fuel model code	Fuel load (Mg/ha) 1-h	10-h	100-h	Live herb	Live woody	Model type	SAV ratio (m^{-1}) Dead 1-h	Live herb	Live woody	Fuel bed depth (cm)	Dead moisture extinction (%)	Heat content (J/g)	Wind adjustment factor
BU0	0.10	1.00	0.50	0.00	0.00	Static	30,000	–	–	1.5	12	18,622	0.228
BU1	5.00	0.00	0.00	0.50	27.0	Static	13,120	13,120	13,120	20	12	20,000	0.335
FM9	6.54	0.93	0.34	0.00	0.00	Static	8202	–	–	6	25	18,622	0.275

Parameter	First sweep	Second sweep	Third sweep
1-h dead fuel (Mg/ha)	0, 0.2, 0.4, 0.8, 1.2, 2, 3, 4, 5, 7, 10, 15, 20	0–30	0–30
10-h dead fuel (Mg/ha)	0, 1, 5, 10, 20, 30	0–40	0
100-h dead fuel (Mg/ha)	0, 1, 5, 10, 20, 30	0–40	0
Live herb (Mg/ha)	0, 0.5, 1, 2, 5, 10, 20	0	0–20
Live woody (Mg/ha)	0, 1, 3, 5, 10, 20	0	0–50
1-h SAV ratio (m^{-1})	1000, 2000, 4000, 6000, 8000, 11,000	1000–40,000	13,120
Live herb SAV ratio (m^{-1})	4000, 6000, 8000	0	13,120
Fuel depth (cm)	0.1, 1, 3, 5, 12, 20, 30, 40, 60, 100, 200	0.1–150	0.1–150
Heat content (J/g)	15,000, 20,000, 25,000	18,622	15,000, 20,000, 25,000
Fuel moisture scenario	Low[A], very low[B]	Very low	Very low
Wind speed (km/h)	0, 5, 10, 20, 30, 40, 50, 60, 70, 80	0, 5, 10, 20, 30, 40, 50, 60, 70, 80	0, 5, 10, 20, 30, 40, 50, 60, 70, 80
Description	Evaluated the full predictive space and response to weather.	Optimal parameter set regardless of feasibility. Expanded range in certain parameters relative to the first sweep. Reference for third sweep to match.	Optimal parameter set implementable in current fire modelling systems.

The BU0 model resulted from the second parameter sweep. The BU1 model resulted from the third parameter sweep that was informed by parameter range restrictions in current software implementations. The FM9 model was the best-matching standard wildland FBFM for use in software that does not allow custom FBFMs. SAV, surface area to volume ratio.
[A]Low Fuel Moisture Scenario defined as 6, 7, 8, 60, and 90% for 1, 10, 100-h, live herbaceous, and live woody percent moisture content, respectively.
[B]Very Low Fuel Moisture Scenario defined as 3, 4, 5, 30, and 60% for 1, 10, 100-h, live herbaceous, and live woody percent moisture content, respectively.

a maximum spread rate of 0.39 km/h. The best fit standard fuel model is Hardwood Litter (FM9), of the original Anderson 13 fuel models (Anderson 1982), which differed from BU0 at RMSE of 0.14 km/h and mean positive bias of 0.09 km/h for RoS in the 'very low' fuel moisture scenario.

The difference between BU1 and FM9 is larger at lower wind speed and higher fuel moisture (Fig. 1, upper right). Therefore, an advantage of the BU1 model over FM9 is slower spread in less aggressive burn conditions. The BU1 model is sensitive to fuel moisture given that the maximum RoS is approximately half as fast under the low moisture scenario compared to the very low scenario if the wind limit is imposed. Modifying fuel moisture for individual FBFMs can be used to calibrate RoS in practice (Stratton 2009). The BU1's low moisture of extinction (12%) in combination with the effective wind limit ensures minimal to no spread in more moist conditions, while the standard FM9 has a higher moisture of extinction (25%) without the low intensity to trigger an effective wind limit leading to much faster RoS in moister conditions that would not be expected to sustain an urban conflagration.

The models were developed without consideration of crown fuels and therefore without the related crown and spot fire propagation models, which represent a typical and perhaps dominant fire spread mechanism in urban environments (Koo *et al.* 2010; Maranghides *et al.* 2013; Roberts *et al.* 2021; Barrett 2024). This is considered a feature for most situations because calibration of crown fire thresholds is not needed, RoS contributions due to short-range spotting are integrated into the surface RoS estimates, which matches the observational dataset, and a deterministic model without spotting is easier to diagnose and calibrate. The primary downsides are that fire propagating from these burnable urban areas cannot spot over other nonburnable barriers, such as water, in fire simulations and not explicitly modelling this important spread mechanism.

Comparisons to urban-specific fire models are difficult given disparities in input parameters, model design, and the specifics of the test areas, such as density and arrangement of combustible material, but even so, the RoS predictions compare favourably to published values. Himoto and Tanaka (2008) predicted 0.14 km/h RoS at 36 km/h windspeed with their physics-based, urban-specific model and reported 0.12 km/h using the foundational Hamada urban spread model, which are 20% larger than the BU0 model prediction (0.10 km/h) and 48% smaller than BU1 (0.23 km/h). Two RoS estimates from case studies using the empirical SWUIFT model (Masoudvaziri *et al.* 2021) are 0.33 and 1.2 km/h at windspeeds of 36.9 and 41.6 km/h, respectively. The 1.2 km/h RoS is larger than all predictions here including the fire spread target (0.81 km/h), but the 1.2 km/h prediction had a large proportion of wildland fuel in that specific landscape – a common confounding factor that makes distinguishing the effect of burnable urban inclusion difficult. The 0.33 km/h prediction from the SWUIFT model is 254% larger than BU0 (0.13 km/h), 32% larger than BU1 (0.25 km/h), and 6% smaller than FM9 (0.35 km/h).

The critical thresholds that dictate when urban areas transition from fire barriers to spread vectors are knowledge gaps. Mechanisms of propagation are difficult to efficiently represent, data varies in scale and quality, and urban conflagrations propagate differently than fire in wildland environments (Rhem *et al.* 2002; Rhem and Mell 2009; Caton *et al.* 2016). Even the assumption of wind-dependent RoS is not well-established in these environments and the observational dataset here did not correlate with observations from nearby weather stations. However, models directly addressing urban spread all have wind as a primary factor in spread (Himoto and Tanaka 2008; Mahmoud and Chulahwat 2018; Masoudvaziri *et al.* 2021; Purnomo *et al.* 2024) with the wind response arguably more refined than the influence of the currently basic fuel inputs to the models (Young *et al.* 2025). Current Rothermel systems are also poor at determining initiation and cessation of fire spread and generally operate under the assumption that fire will spread (Finney *et al.* 2013; Caton *et al.* 2016), perhaps most epitomised by the current need for the manual definition of a daily burn period (Finney 2006; Cochrane *et al.* 2011).

Of course, the empirical foundation of the Rothermel model necessitates critical evaluation of any extrapolation beyond the original conditions. For emergency planning, simulations that include burnable urban models could be viewed as extreme scenarios and then paired with standard simulations using non-burnable urban areas. The fire modelling community will ultimately determine this stopgap solution's usefulness through application.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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