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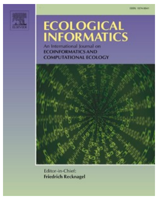

Modelling fire behaviour in the lodgepole pine forests of interior British Columbia: An evaluation of models against field evidence

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Preface: As wildfire threats intensify, forest managers rely on computer models to predict fire behaviour. This study shows that while some models work well in natural forests, they often fail in areas altered by logging. Improving these tools is key to safer, more effective wildfire planning.

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Mountain pine beetle
Ladder fuels
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ABSTRACT

Fire behaviour models are increasingly used to guide wildfire management decisions, yet few have been rigorously validated with field-based evidence. Following a 2017 wildfire, we evaluated four fire behaviour models in natural and irregular shelterwood–treated lodgepole pine stands in interior British Columbia by comparing modelled against field-reconstructed head fire intensity (HFI) under recorded fire-weather scenarios. The Canadian Conifer Pyrometrics (ConPyro) model, when ladder fuels were included, produced predictions that closely matched reconstructed head fire intensity at the 75th wind percentile, with a mean absolute quantile distance (MAQD) of 1407 kW m^{-1} across quantiles. Crown Fire Initiation and Spread (CFIS) predictions exhibited higher variance, with MAQD values ranging from 4545 to 7470 kW m^{-1}. The Canadian Forest Fire Behaviour Prediction (FBP) System (C2 and C3 fuel types) showed strong sensitivity to wind speed, resulting in large variability in predicted intensity. In contrast, BehavePlus consistently underestimated HFI (MAQD = 11,387 kW m^{-1}, $p < 0.01$). In treated stands, all models either over- or underestimated HFI relative to reconstructed values, reflecting limited applicability in forests with discontinuous canopy structure. Overall, ConPyro performed adequately in natural conifer stands when ladder fuels were included, whereas all current models inadequately represented the spatial discontinuity and structural complexity created by treatments. These findings highlight the need to explicitly incorporate canopy structure into future model development to improve fire behaviour predictions in both natural and managed forests.

List of abbreviations

BEC	Biogeoclimatic Ecosystem Classification
BehavePlus	Fire behaviour prediction software
BC	British Columbia
BUI	Buildup Index
CAC	Criterion for Active Crowning
CBD	Canopy Bulk Density
CBH	Crown Base Height
ConPyro	Canadian Conifer Pyrometrics
CFC	Crown Fuel Consumption
CFL	Canopy Foliage Load
CFB	Crown Fraction Burned
CFIS	Crown Fire Initiation and Spread
CROS	Crown Rate of Spread
DMC	Duff Moisture Code
DC	Drought Code
DBH	Diameter at Breast Height
DCBH	Dead Crown Base Height
FBP	Fire Behaviour Prediction System
FFL	Forest Floor Load
FSG	Fuel Strata Gap
GFL	Grass Fuel Load
HFI	Head Fire Intensity
hFFMC	Hourly Fine Fuel Moisture Code
hFWI	Hourly Fire Weather Index
hISI	Hourly Initial Spread Index
hRH	Hourly Relative Humidity
hTemp	Hourly Temperature
hWD	Hourly Wind Direction
hWS	Hourly Wind Speed
IB	Fireline Intensity
MSxv	Montane Spruce very dry very cold variant

(*continued on next page*)

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(*continued*)

ROS	Rate of Spread
SFC	Surface Fuel Consumption
SROS	Surface Rate of Spread
TSA	Timber Supply Area
VRI	Vegetation Resource Inventory
WFL	Woody Fuel Load
WS	Wind Speed
wsPercentile	Wind Speed Percentile

1. Introduction

Wildfires in North America have intensified over recent decades, both in the magnitude of individual events and the frequency of extreme fire activity (Iglesias et al., 2022). This escalation is largely attributed to rising temperatures, extended fire seasons, and early snowmelt associated with ongoing climate change (Abatzoglou and Park Williams, 2016; Westerling, 2016). These changes have posed significant challenges to ecological, economic, and social systems (Calkin et al., 2014; Hessburg et al., 2005). In Canada, wildfires burned an annual average of 1.96 Mha between 1959 and 2015, but fire activity has intensified markedly since then (Flannigan et al., 2016; Parisien et al., 2023), with a national average of 4.09 Mha burned annually from 2016 to 2023 (Natural Resources Canada, 2023). The 2023 wildfire season currently stands as the most damaging on record, with fires having affected 16.5 million hectares of the land base (Jain et al., 2024). In British Columbia (BC), the 2023 fire season alone impacted more than two million hectares, representing a record-breaking annual total (Daniels et al., 2025).

Historical silviculture practices and prolonged wildfire suppression have contributed to fuel accumulation and increases in fire intensity and severity (Baron et al., 2022; Brookes et al., 2021). Under these increasingly sever fire regimes, understanding wildland fire behaviour, particularly during extreme events, is critical for ensuring firefighter safety, protecting communities, and guiding fuel management strategies and other proactive mitigation measures (Taylor et al., 2013). Advances in fire behaviour modelling have substantially improved the ability of researchers and land managers to predict fire activity under specific combinations of fuel, topography, and weather and moisture conditions.

Wildland fire behaviour models are commonly classified into physical and quasi-physical models, empirical and quasi-empirical models, and simulation or mathematical analogue models (Sullivan, 2009a, 2009b, 2009c). Physical and quasi-physical models support detailed scientific investigation but are rarely used operationally because of their high data requirements, computational demands, and limited reliability at management timescales. In contrast, empirical and quasi-empirical models are favoured in operational contexts due to their ease of use, making them suitable for real-time decision-making (Sullivan, 2009a, 2009b, 2009c). Prominent operational fire behaviour models in Canada and the United States include the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992), Crown Fire Initiation and Spread (CFIS) System (Alexander et al., 2006a), Canadian Conifer Pyrometrics (ConPyro) (Perrakis et al., 2020), and BehavePlus (Andrews et al., 2005).

Despite their widespread application, the accuracy of operational fire behaviour models remains a subject of ongoing debate. Because model outputs are frequently used to inform suppression strategies, evacuation decisions, and fuel management planning, prediction errors can have serious consequences for firefighter and public safety. Discrepancies between modelled and observed fire behaviour may arise from limitations in model structure, inappropriate application contexts, or uncertainty and bias in model input data (Alexander and Cruz, 2013b). Model evaluation studies remain relatively scarce, and few have identified consistently accurate predictions across diverse fire environments (Alexander and Cruz 2013). Moreover, recent research has documented a strong underprediction bias in commonly used United States fire behaviour models, including NEXUS (Scott and Reinhardt, 2001), FFE-FVS (Reinhardt and Crookston, 2003), FARSITE (Finney, 1998b), FMAPlus (Carlton, 2005), FlamMap (Finney, 2006), and BehavePlus (Andrews et al., 2005). This bias has been attributed to: (1) incompatible model linkages between canopy base height calculations and Van Wagner's critical surface fire intensity model; (2) the application of surface and crown fire rate of spread models which intrinsically tend toward underprediction; (3) a decrease in predicted crown fire rate of spread due to a “blending” of surface and crown fire rates of spread; and (4) the use of uncalibrated custom fuel models (Cruz and Alexander, 2010).

Accurate fire behaviour prediction is further complicated by the stochastic nature of wildfires, limited availability of high-resolution fire environment data, and challenges associated with reconstructing fuel and weather conditions during active fire periods (Finney, 1998a). Consequently, the rate at which fire behaviour models are applied in operational and research settings has outpaced their systematic evaluation, leading to persistent concerns about model misapplication overconfidence in model outputs (Alexander and Cruz, 2013a).

This study presents a unique opportunity to evaluate the performance of contemporary fire behaviour models using field-based evidence from a wildfire that burned through a stand treated with an irregular shelterwood silvicultural system in 2017, in interior BC. Building on previous work from the same study area (Liu et al., 2024), this research assesses the accuracy and applicability of four widely used and emerging fire behaviour models – FBP, CFIS, ConPyro, and BehavePlus – in lodgepole pine forests. Specifically, the study aims to (1) retrospectively reconstruct pre-fire fuel conditions and observed head fire intensity using post-fire field measurements, (2) generate modelled head fire intensity under a range of representative fire-weather scenarios, and (3) compare modelled and reconstructed fire intensity in both untreated and treated stands. Given the discontinuous canopy structure created by the irregular shelterwood treatment, this study also evaluates the extent to which existing models can represent fire behaviour in managed forests with complex spatial structure. The results contribute to a growing body of evidence on model performance in interior BC, and provide insights to inform future model development and refinement.

2. Materials and methodology

2.1. *Study site*

The study site is located 100 km west of the city of Quesnel, BC, Canada, within the Quesnel Timber Supply Area (TSA), at an elevation of 1300 m above sea level (Fig. 1). Forests at the site are dominated by lodgepole pine *(Pinus contorta),* hybrid spruce *(Picea engelmannii x glauca)* and subalpine fir *(Abies lasiocarpa),* with Douglas-fir (*Pseudotsuga menziesii*) and trembling aspen *(Populus tremuloides)* occurring as sub-dominant species (Meidinger and Pojar, 1991). Topographic variability across the study area is minimal, indicative of a planar terrain. Lodgepole pine forests in the surrounding region experienced approximately 50–60% mortality associated with mountain pine beetle outbreaks in the early 2000s.

Within the 250 ha study area, forest structure consisted of a largely even-aged lodgepole pine overstory, with minor components of hybrid spruce (10%), and stand ages ranging from 120 and 150 years old (B.C. Ministry of Forests, 2021a). In 2012, a 100-ha portion of the study area was harvested using an irregular shelterwood silvicultural system that created 50% canopy openings arranged in a checkerboard pattern (Fig. 1). Harvest openings were 0.15 ha (30 m × 50 m) in size and were interspersed with retention patches of the equal size to provide canopy shelter. Wood was extracted using three main skidding trails oriented northeast to southwest, which divided the harvest block into four sections, and connected to landings in an adjacent plantation to the northeast.

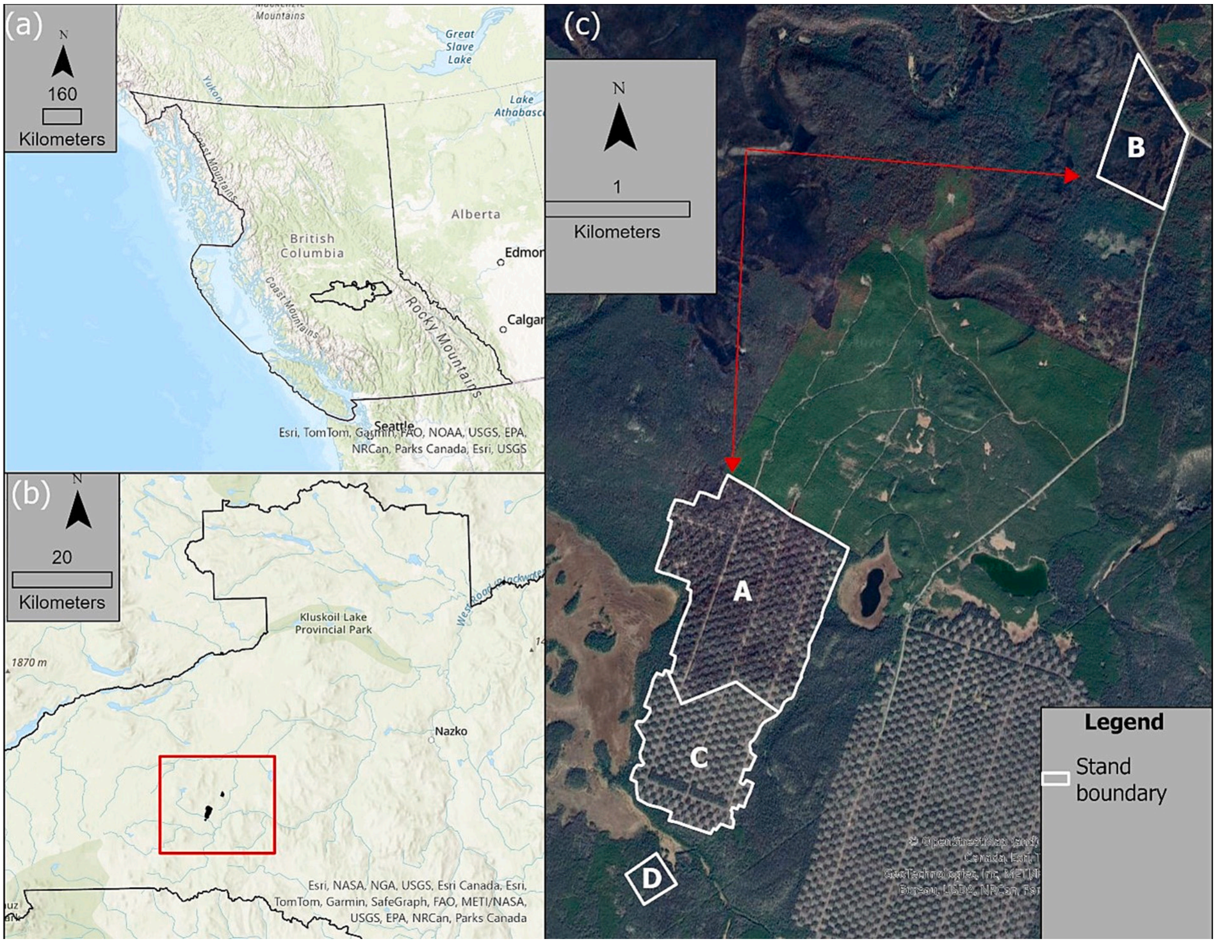

Fig. 1. (a) Province boundary of BC and Quesnel TSA (b) Location of study site in Quesnel TSA (c) Stand boundaries of study site. Red arrows show the spread direction of the wildfire in 2017. Stand type: A: treated-burned; B: untreated-burned; C: treated-unburned; D: untreated-unburned. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. *Fire dynamics and stand selection*

Landsat imagery acquired during the summer of 2017 indicates that a wildfire originating northwest of the study site approached the area and subsequently divided into two distinct fire heads (Fig. 1c). This fire event provided an opportunity to examine the effects of irregular shelterwood harvest structure on wildfire behaviour in interior lodgepole pine forests (Liu et al., 2024). The absence of detailed ground-based fire progression records precluded precise determination of fire arrival times at individual stands or plots. However, available aerial photography and satellite imagery allowed for estimation of fire spread over several days. A Landsat image dated August 4, 2017, shows the fire reaching the edge of the treated stand, while an image from August 12, 2017, shows active burning in the treated-burned stand, and encroachment into the untreated-burned stand at the northwest corner (Fig. 2)(Landsat-8 Image Courtesy of the U.S. Geological Survey, 2026)

Additional evidence of fire spread and activity was obtained from near-infrared thermal anomaly detections derived from the Fire Information for Resource Management System (FIRMS) and the Canadian Fire Spread Dataset (CFSDS) (Dataset S1, Fig. S1 (1−10)) (Barber et al., 2024; NASA VIIRS Land Science Team, 2020) . Based on these data sources, the fire was inferred to have burned through the treated stand between August 5–12, 2017, and through the untreated stand primarily on August 12, 2017.

Historical B·C. Vegetation Resources Inventory (VRI) data from 2016 were used to identify nearby unburned stands with similar attributes to the treated-burned and untreated-burned stands, respectively, to estimate pre-fire fuel conditions. Treated-burned stands were paired with treated-unburned stands (Table 1). Two assumptions were made: (1) that unburned stands adequately represented the pre-fire fuel conditions of their burned counterparts, and (2) that pre-fire fuel loading and structure were comparable between treated-unburned retention patches and untreated-unburned stands.

2.3. *Fire behaviour model selection*

The Canadian Forest Fire Behaviour Prediction (FBP) System, Crown Fire Initiation and Spread (CFIS), and Canadian Conifer Pyrometrics (ConPyro) were selected for evaluation because they are widely used and emerging Canadian fire behaviour models developed from experimental fires and wildfire observations across a range of Canadian forest types. The FBP System (Forestry Canada Fire Danger Group, 1992; Wotton et al., 2009) is the primary operational model used in Canada for fire behaviour prediction, fire danger assessment, and related applications (Erni et al., 2024; Johnston et al., 2020; Taylor and Alexander, 2006). Based on field observations and stand characteristics, the C2 and C3 fuel types were selected for FBP simulations, as they most closely represented the conditions of the study stand (Perrakis et al. 2018; Lacarte 2024).

CFIS is an empirically based crown fire modelling framework that incorporates contemporary models for predicting crown fire initiation and spread in conifer forests, and has been evaluated against experimental and wildfire datasets (Alexander et al., 2006b). ConPyro is an emerging system for simulating fire behaviour in conifer forests that

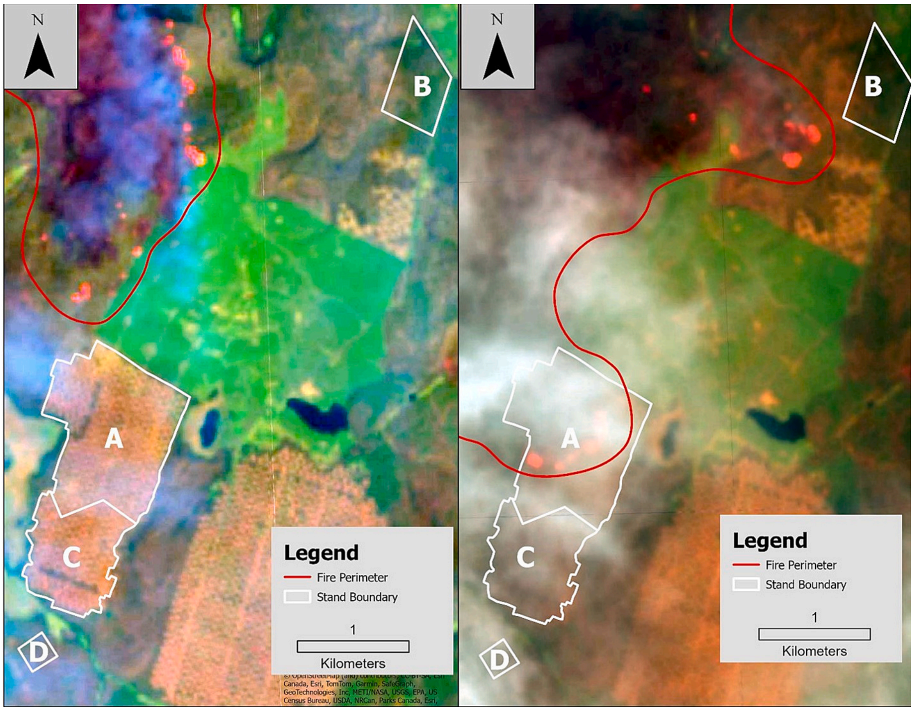

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Fig. 2. Landsat photos on 2017 August 4th(left) and 12th(right). A: treated-burned, B: untreated-burned, C: treated-unburned, D: untreated-unburned stand. The flames are visible in this photo. Fire perimeter is inferred based on the pattern of flames.

Table 1
Stand attributes before fire event in 2016 (B.C. Ministry of Forests, 2021b).

Stand Type	Code	Species composition (%)		Live tree density (stems/ha)	Dead tree density (stems/ha)	Age (yr)
		Pli	Sx			
Treated-Burned	A	80	20	270	200	128
Untreated-Burned	B	85	15	459	500	143
Treated-Unburned	C	80	20	270	200	128
Untreated-Unburned	D	100	0	500	600	143

builds upon Canadian experimental and wildfire data and incorporates additional processes, including ladder fuel effects on crown fire initiation, stand influences on fine fuel moisture content, and updated surface fire rate of spread equations (Perrakis et al., 2020; Perrakis and Thompson, 2025; Wotton and Beverly, 2007).

BehavePlus is a widely used fire modelling system that links the semi-physical Rothermel (1972) surface fire spread model with additional models of fire behaviour, fire effects, and fire environment. It was selected to represent a commonly applied United States model used outside of its country of origin (Andrews, 2010). BehavePlus was preferred over other US-based systems because it does not reduce spread rate based on crown fraction burned, resulting in a slightly lower underprediction bias compared to other models from United States(Cruz and Alexander, 2010).

2.4. Model input data collection

2.4.1. Field data collection and calculation

At each sampling plot, fuelbed components were measured using a combination of fixed-radius plots and line-intersect sampling. Eighteen randomly located plots were established across three stand types: treated-unburned retention patches, treated-unburned openings, and untreated-unburned stands, with six plots per stand type. In burned stands, the same plot design was applied, with additional measurements collected to reconstruct fire effects.

Large trees (diameter at breast height [DBH] $\geq$ 12.5 cm) were measured within a 0.04-ha (11.28 m radius) circular fixed-area plot, following established protocols (Gillis et al., 2005). Within each large-tree plot, small trees (DBH $\geq$ 5 cm and $<$ 12.5 cm) were measured in nested 0.01 ha (5.64 m radius) subplots. For all trees, species, condition (live or dead with decay class), DBH, total height, live crown base height (CBH), dead crown base height (DCBH) and crown position (dominant, codominant, intermediate, or suppressed) were recorded. In burned plots, the maximum bole char height was recorded on each tree and used as an indicator of fire intensity for reconstruction analyses.

Surface fuel loads were measured using the line-intersect method based on Canadian size class definitions (Van Wagner, 1968). Canopy cover was recorded every 2 m intervals along transects using a tube densitometer (Jennings et al., 1999) and converted to percentage cover. Grass fuel load (GFL) was estimated withing a 0.01-ha circular subplot established at the end of each fuel transect. Grass species were identified, and percent cover and height were visually estimated using the Photoload method; these metrics were used to calculate plot-level GFL (Keane and Dickinson, 2007).

Canopy fuel load (CFL) for individual live conifer trees was calculated using Canadian national species-specific biomass equations relating foliage biomass to DBH and height (Ung et al., 2008). Tree-level CFL estimates were calculated for large trees, small trees, and saplings, scaled to a per-hectare basis, and summed to derive stand-level CFL, considering only live coniferous trees. While available canopy fuels include small branchwood and foliage (Stocks et al., 2004), only foliage biomass was included in CFL estimates to remain consistent with the assumptions of the evaluated models (Cruz et al., 2005; Perrakis et al., 2020; Van Wagner, 1977). Tree-level CFL values from the three tree categories were then summed within each plot to derive stand-level CFL. Canopy bulk density (CBD) was calculated by dividing tree-level CFL by crown depth.

Forest floor load (FFL) was estimated as the sum of duff and litter loads within each plot. Average bulk density values of 125.33 kg m^{-3} for duff and 48.73 kg m^{-3} for litter were applied, based on published values for stands composed of 80% lodgepole pine and 20% hybrid spruce (Woodall and Monleon, 2008). Plot-level duff and litter loads were calculated by multiplying average depths, measured at 7.5 m and 22.5 m along fuel transects, with the average loading values. Data from all plots, burned and unburned, were used to derive model input parameters. Summary statistics for plot-level variables are presented in Table 2.

2.4.2. Single- and multi-layer canopy fuel calculations

For ConPyro (simple canopy configuration), CFIS, and BehavePlus simulations, CBH was calculated as the basal-area-weighted mean of measured overstory and midstory CBH values to reduce disproportionate influence from small trees with limited crown development (e.g., DBH < 5 cm; Liu et al., 2024).

ConPyro also allows explicit representation of ladder fuel influences and multi-layer canopy structures. For simulations incorporating ladder fuels (‘ConPyro Ladder’ simulations), both dead ladder fuels and live midstory trees were included following published and operational procedures (Perrakis et al., 2023; Perrakis and Thompson, 2025). These calculations allowed simulation of sequential crowning in two-layer stands. Additional methodological details are provided in the supplementary information.

2.4.3. Fire weather data collection

Hourly weather data for inferred fire dates was obtained from the nearest BC Wildfire Service weather station (BALDFACE), located approximately 20 km to the southeast from the study site. Variables included the hourly Fire Weather Index (hFWI), Buildup Index (BUI), Drought Code (DC), Duff Moisture Code (DMC), hourly Fine Fuel Moisture Code (hFFMC), hourly Initial Spread Index (hISI), relative humidity (hRH), temperature (hTemp), wind speed (hWS), and wind direction (hWD) (B.C Wildfire Service, 2023). Station data were assumed to be representative of site-level conditions.

Because the exact timing of fire arrival at each plot could not be determined, three hourly weather scenarios were selected for each day between 5th and 12th August 2017, corresponding to the 50th (median), 75th percentile, and maximum wind speeds between 12:00 and 23:00. This time window was selected because previous research indicates that fireline intensity typically increases through late morning, peaks in the afternoon, and declines toward evening, thereby better representing potential peak burning conditions (Li et al., 2025). Weather variables used in the model simulations are summarized in Table 3.

All variables listed in Tables 2 and 3 were used for FBP, CFIS, and ConPyro modelling. For FBP, all plots were simulated using the C2 and C3 fuel types, as noted. For BehavePlus, each plot was assigned a standard fire behaviour fuel model based on measured woody fuel load (Prichard et al., 2013; Scott and Burgan, 2005). Due to extreme drought conditions during August 2017, BehavePlus simulations used the d111 moisture scenario (very low, fully cured herb), with foliar moisture fixed at 100% in accordance with user guide recommendations.

2.5. Fire behaviour modelling

This study evaluated the estimated accuracy of four fire behaviour models. The overall structure of ConPyro has been previously described (Perrakis et al., 2020), and detailed modelling procedures for ConPyro and CFIS are provided in the supplementary information.

FBP simulations were conducted using standard system equations with inputs derived from Tables 2 and 3 to generate head fire intensity (HFI) predictions. The FBP modelling workflow followed established operational procedures and is documented elsewhere (Forestry Canada Fire Danger Group, 1992; Wotton et al., 2009). BehavePlus simulations were conducted using version 6.0.0 without modification, following methods outlined by Heinsch and Andrews (2010) and Andrews (2018). In contrast to Canadian models, BehavePlus simulations were conducted manually and were therefore limited to maximum wind speed scenarios (Table 3). Selected modules and sub-modules used in BehavePlus are detailed in Appendix 1. The primary differences between modelling systems are summarized in Table 4.

2.6. Fire intensity reconstruction and analysis

During the summer of 2023, eighteen large-tree plots and eighteen nested subplots were established in the two burned stands to document tree status (live or dead), species, DBH, and maximum char height. All char measurements were attributed to the 2017 wildfire, as no evidence of earlier or subsequent fire events was present. Flame length was first estimated from maximum char height using an empirical relationship, and fireline intensity was then calculated using the rearranged flame length equation of Thomas (1963), as follows:

$$L = \text{Char height}^{*}\ 1.8 \tag{2}$$

$$\text{IB} = \left(\frac{L}{0.0267}\right)^{\frac{3}{2}} \tag{3}$$

where L is flame length (m), I_B is fireline intensity (kW m^{-1}).

Reconstructed HFI distributions were compared with model-predicted HFI under each wind-speed percentile. Because BehavePlus predictions were only available for the maximum wind speed, compar-

Table 2
Summary of field data as fire behaviour model inputs.

	Untreated-Unburned				Treated-Unburned			
variable	mean	min	max	SD	mean	min	max	SD
CC (%)*	36	20	60	15.01	34	20	53	13.01
DENS (ha^{-1})	1538	250	5850	2141.48	807	250	3250	1087.11
CFL (kg m^{-2})	0.29	0.15	0.44	0.13	0.33	0.24	0.43	0.07
CBD (kg m^{-3})*	0.04	0.01	0.07	0.02	0.04	0.02	0.07	0.02
HT (m)*	11.08	6.24	13.66	2.75	12.80	8.72	17.13	2.89
CBH (m)*	3.91	0.91	7.19	2.20	2.66	0.72	4.78	1.26
CBH (Layer 1) (m)$^{+}$	4.02	0.96	7.19	2.18	3.77	2.24	6.06	1.42
CBH (Layer 2) (m)$^{+}$	0.46	0	0.91	0.64	0.36	0	0.8	0.29
FFL (kg m^{-2})	3.41	0.76	5.56	1.80	4.58	2.72	6.55	1.41
WFL (kg m^{-2})	0.14	0.03	0.24	0.07	0.77	0.22	1.79	0.67

Note: CC: Canopy cover (%),DENSs: tree density (stems haˆ-1), CFL: crown fuel loading (kg mˆ-2), CBD: canopy bulk density (kg mˆ-3), HT: average live tree height (m), CBH: average live crown base height, FFL: estimated forest floor loading (kg mˆ-2), WFL: measured woody fuel loading (kg mˆ-2).

*FBP, CFIS and ConPyro models require all listed input variables; BehavePlus only uses variables marked *. $^{+}$*CBH specified by layer are required input by ConPyro Ladder only.*

Table 3
Weather data input from 2017 Aug 5th to Aug 12th.

day	hTemp	hRH	hWS	hWD	wsPercentile	hFFMC	DMC	DC	hISI	BUI	hFWI
5	23.0	22	6.6	326	50th	88.3	103	499	4.7	136	21.2
5	23.2	22	8.4	41	75th	91.3	103	499	7.9	136	30.4
5	23.3	21	11.8	358	Max	89.3	103	499	7.0	136	28.1
6	25.4	21	7.1	162	50th	89.4	108	507	5.6	141	24.4
6	25.4	21	7.9	70	75th	91.0	108	507	7.3	141	29.3
6	24.0	22	16	27	Max	91.5	108	507	11.9	141	40.4
7	21.6	32	5.5	28	50th	90.7	111	514	6.3	144	26.5
7	24.3	26	8.4	90	75th	89.4	111	514	6.0	144	25.8
7	23.8	31	11.3	84	Max	88.7	111	514	6.3	144	26.5
8	22.7	30	6.6	64	50th	90.6	115	521	6.5	148	27.5
8	24.7	27	8.2	68	75th	88.5	115	521	5.2	148	23.5
8	24.2	27	10	54	Max	90.4	115	521	7.5	148	30.2
9	23.9	31	5.9	123	50th	86.2	118	529	3.3	152	17.2
9	25.2	28	6.1	162	75th	87.2	118	529	3.9	152	19.3
9	25.0	32	10.1	27	Max	90.3	118	529	7.4	152	30.3
10	26.0	23	4.8	158	50th	91.3	123	536	6.6	156	28.1
10	26.9	22	6.3	138	75th	87.8	123	536	4.3	156	20.9
10	27.3	21	10.3	158	Max	89.1	123	536	6.4	156	27.4
11	28.9	13	10	249	50th	93.4	127	544	11.5	161	41.0
11	28.1	17	13.1	194	75th	89.3	127	544	7.5	161	31.0
11	29.4	9	14.2	239	Max	92.5	127	544	12.6	161	43.4
12	25.2	21	15.8	181	50th	90.4	132	552	10.0	165	37.6
12	20.8	19	19.4	190	75th	92.8	132	552	17.0	165	52.7
12	23.0	22	20.9	182	Max	91.6	132	552	15.3	165	49.5

Note: day: Day within August 2017; hTemp: hourly temperature (°C); hRH: hourly relative humidity (%); hWS: hourly wind speed 10 m above the ground (m/s); hWD: hourly wind direction (°); wsPercentile: hourly wind speed percentile of the time window (12 pm to 11 pm) of the day; hFFMC: hourly fine fuel moisture content; DMC: daily duff moisture content; DC: daily drought code; hISI: hourly initial spread index; BUI: daily build up index; hFWI: hourly fire weather index; BUI: build up index.

Table 4
Summary of key modules and submodules for assessed models.

Module	Sub-module	ConPyro	CFIS	FBP	BehavePlus
Surface Fire Module	*Surface fuel consumption*	Forest floor consumption model (de Groot et al. 2009) + measured woody fuel loading (<7 cm diam.)	Fuel type specific consumption model (Forestry Canada Fire Danger Group, 1992)	Fuel type specific consumption model (Forestry Canada Fire Danger Group, 1992)	Standard fuel models (Anderson, 1982; Scott and Burgan, 2005)
	Surface ROS	Conifer model Eq. 9 (Perrakis and Taylor, 2025)	Conifer model Eq. 9 (Perrakis and Taylor, 2025)	Fuel bed specific ROS equation (Forestry Canada Fire Danger Group, 1992)	Rothermel surface ROS equation (Rothermel, 1972); (Albini, 1976) minor adjustments
Crown Fire Module	*Crown fire occurrence model*	Perrakis et al. (2023)	Cruz et al. (2004; See also Supplemental material)	Critical surface fire intensity theory (Van Wagner, 1977)	Critical surface fire intensity theory (Van Wagner, 1977); Transition to crown fire, relationship of surface fire intensity and critical surface fire intensity (Van Wagner, 1993; Finney, 1998b; Scott and Reinhardt 2001)
	Crown ROS	Passive and active crown ROS (Cruz et al., 2005; Supplemental material)	Passive and active crown ROS (Cruz et al. 2005; Supplemental mat.)	Fuel type specific ROS equation (Forestry Canada Fire Danger Group, 1992)	Rothermel crown fire ROS (Rothermel, 1991)
	Crown fuel consumption	Canadian CFC (Forestry Canada Fire Danger Group, 1992)	Canadian CFC (Forestry Canada Fire Danger Group, 1992)	Canadian CFC (Forestry Canada Fire Danger Group, 1992)	N.A. (BehavePlus does not calculate crown fuel consumption)
Head fire intensity	*Surface fire*	(Byram, 1959)	(Byram, 1959)	(Byram, 1959)	(Byram, 1959) with adjustments to work with Rothermel's surface fire spread model by (Albini Frank, 1976b)
	Crown fire				(Rothermel, 1991)

isons for this model were limited accordingly. Differences between predicted and reconstructed HFI distributions were assessed using quantile regression across selected quantiles ($\tau = 0.50, 0.75, 0.90$). Model performance was summarized using the mean absolute quantile distance (MAQD) between predicted and reconstructed HFI across quantiles (step = 0.05), following Barros et al. (2019). Smaller MAQD values indicate closer agreement between modelled and reconstructed fire intensity distributions.

3. Results

3.1. Predicted HFI, untreated stand

Modelled and reconstructed head fire intensity (HFI) values for the untreated stand are presented in Fig. 3, illustrating differences among fire behaviour models, wind-speed percentile scenarios (median, 75th, and maximum), and crown fire occurrence predictions.

3.1.1. ConPyro

The simple canopy ConPyro predictions showed reasonable agreement with reconstructed HFI at 75th and maximum wind percentiles (MAQD = 1774 and 1720 kW m^{-1}). However, the upper tail of

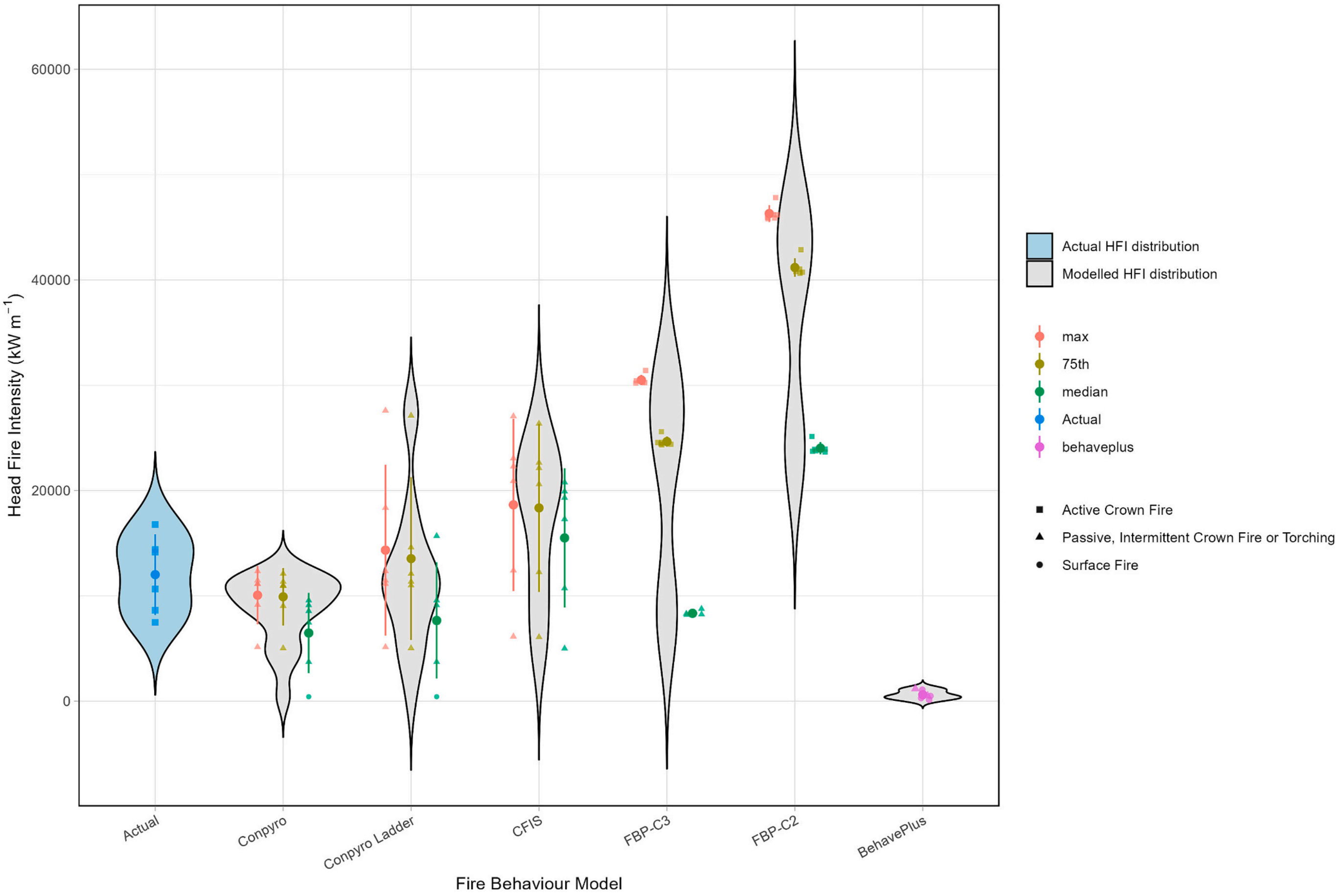

Fig. 3. Summary of modelled fire intensity vs reconstructed fire intensity in untreated stand. The left-most group shows the HFI range and distribution pattern for reconstructed HFI in untreated-burned stand (sec. 2.6). ConPyro, CFIS and FBP were tested modelled at median, 75th and max wind speed weather data. Behaveplus was only run to predict HFI at the maximum wind speed. Each violin shows the HFI range and distribution pattern of prediction from all plots, with jitters showing the exact predictions at each plot.

reconstructed HFI distribution was underestimated in both cases at 0.9 quantile (difference = −4670 and − 4430 kW m^{-1}, $p < 0.05$). At the median wind speed, ConPyro significantly underestimated HFI at both the 0.75 and 0.9 quantiles (difference = −5279 and − 7208 kW m^{-1}, $p < 0.05$). Incorporating the ladder fuel function to represent the two-layer canopy structure of lodgepole pine and hybrid spruce shifted modelled HFI upward across wind-speed percentiles. Including ladder fuels improved ConPyro model performance at higher wind speeds, enabling the model to capture the upper tail of reconstructed HFI at the 75th and maximum wind percentiles (Table S1). Overall, ConPyro with ladder fuels achieved the lowest MAQD at the 75th wind percentile (1407 kW m^{-1}), providing the closest overall match to the reconstructed HFI distribution (Table S3).

3.1.2. *CFIS*

CFIS predictions exhibited distributions broadly similar in shape to ConPyro with ladder fuels, but deviated more strongly from reconstructed HFI values. Across wind-speed percentiles, CFIS produced consistently larger errors (MAQD = 4546–7470 kW m^{-1}). Relative to ConPyro with ladder fuels, CFIS showed a pronounced overestimation bias in the upper tail of the distribution, particularly at 0.75 and 0.9 quantiles, where predicted HFI exceeded reconstructed values by more than 4000 kW m^{-1} ($p < 0.05$; Table S1).

3.1.3. *FBP*

FBP produced the widest range of HFI predictions among all models, spanning from approximately 8321 to values exceeding 45,000 kW m^{-1}. Overall, FBP predictions differed substantially from the reconstructed HFI distribution, with large distributional errors and showed large errors across all wind-speed percentiles. Using the C2 fuel type, HFI was consistently and strongly overestimated, with significant positive quantile differences at $\tau = 0.5$–0.9 (9626 to 31,796 kW m^{-1}; $p < 0.001$) and the largest MAQD values overall (11,903–34,128 kW m^{-1}; Tables S1 and S3). Using the C3 fuel type reduced predicted HFI magnitude relative to C2 but still produced substantial mismatch. HFI was significantly overestimated at the 75th and maximum wind percentiles (8812 to 16,132 kW m^{-1}; $p < 0.001$; MAQD = 12,544–18,400 kW m^{-1}), but shifted to significant underestimation at the median wind percentile (−5844 to −8013 kW m^{-1}; $p < 0.05$) (Tables S1 and S3).

3.1.4. *BehavePlus*

BehavePlus produced substantially lower HFI predictions than all other models, with values narrowly clustered around approximately 600 kW m^{-1}. These predictions were far below the reconstructed HFI range, resulting in significant differences ($p < 0.01$) and a large MAQD of 11,387 kW m^{-1} (Tables S2 and S3).

3.2. *Predicted HFI, treated stand retention patches*

Modelled HFI values for treated-unburned retention patches were compared with reconstructed HFI from treated-burned plots over the inferred fire period from 5 to 12 August 2017.

3.2.1. *ConPyro*

ConPyro predictions consistently exceeded reconstructed HFI values across all days and wind-speed percentiles (Fig. 4a). Reconstructed HFI in the treated-burned stand ranged from 430 to 851 kW m^{-1}, whereas modelled predictions were substantially higher across quantiles. Differences were significant in 65 of 72 quantile regression tests ($P < 0.05$; Table S4). Maximum wind percentile scenarios produced the greatest HFI estimates, with predicted values reaching approximately 28,000 kW m^{-1}. Median and 75th percentile predictions were lower than the maximum wind predictions, but still substantially exceeded reconstructed values. Incorporating ladder fuels increased variability and produced higher HFI predictions across wind percentiles (Figs. 4b), but did not meaningfully reduce the degree of overestimation, with predicted ranges remaining well above the reconstructed HFI distribution.

3.2.2. *CFIS*

CFIS consistently produced HFI predictions that substantially exceeded reconstructed values in treated-burned stands across all fire-weather days and wind percentiles (Fig. 4c). While reconstructed HFI ranged from 430 to 851 kW m^{-1}, CFIS predictions typically fell between approximately 10,000 to 29,800 kW m^{-1}. Overestimation was significant in all 72 quantile regression tests ($P < 0.05$; Table S4). Maximum wind percentile predictions yielded the highest HFI estimates throughout the period, peaking on August 12th. Median and 75th percentile predictions were lower but still consistently exceeded reconstructed HFI values.

3.2.3. *FBP*

FBP predictions in treated stands were strongly influenced by fuel type selection (Figs. 4d–e). Under the C3 fuel type, predicted HFI values during the earlier portion of the fire-weather period (Aug 5–10) typically ranged from approximately 1500–3200 kW m^{-1} and exhibited greater variability than the other models. A limited number of quantile regression tests were not significant (8 of 72; Table S4), indicating partial overlap with reconstructed HFI on some days and quantiles. Under more extreme conditions on August 11 and 12, however, C3 predictions increased sharply and again substantially overestimated reconstructed HFI, reaching approximately 30,000 kW m^{-1} at upper wind percentiles.

Using the C2 fuel type resulted in consistently higher HFI predictions and near-uniform overestimation throughout the entire period. Predicted HFI ranged from approximately 4000 to 48,500 kW m^{-1}, with the highest values occurring under maximum wind conditions on Aug 12. Even under median wind scenarios, predicted values greatly exceeded reconstructed HFI (Table S4). Overall, fuel type selection strongly influenced FBP outputs, with C3 producing reduced but still excessive predictions and C2 yielding persistent and extreme overestimation.

3.2.4. *BehavePlus*

BehavePlus predictions for treated stands are shown in Fig. 5. Across the August 5–12 period, the model consistently underestimated reconstructed HFI, with differences generally ranging from 37 to 510 kW m^{-1}, and averaging approximately 160 kW m^{-1} (Table S5). Quantile

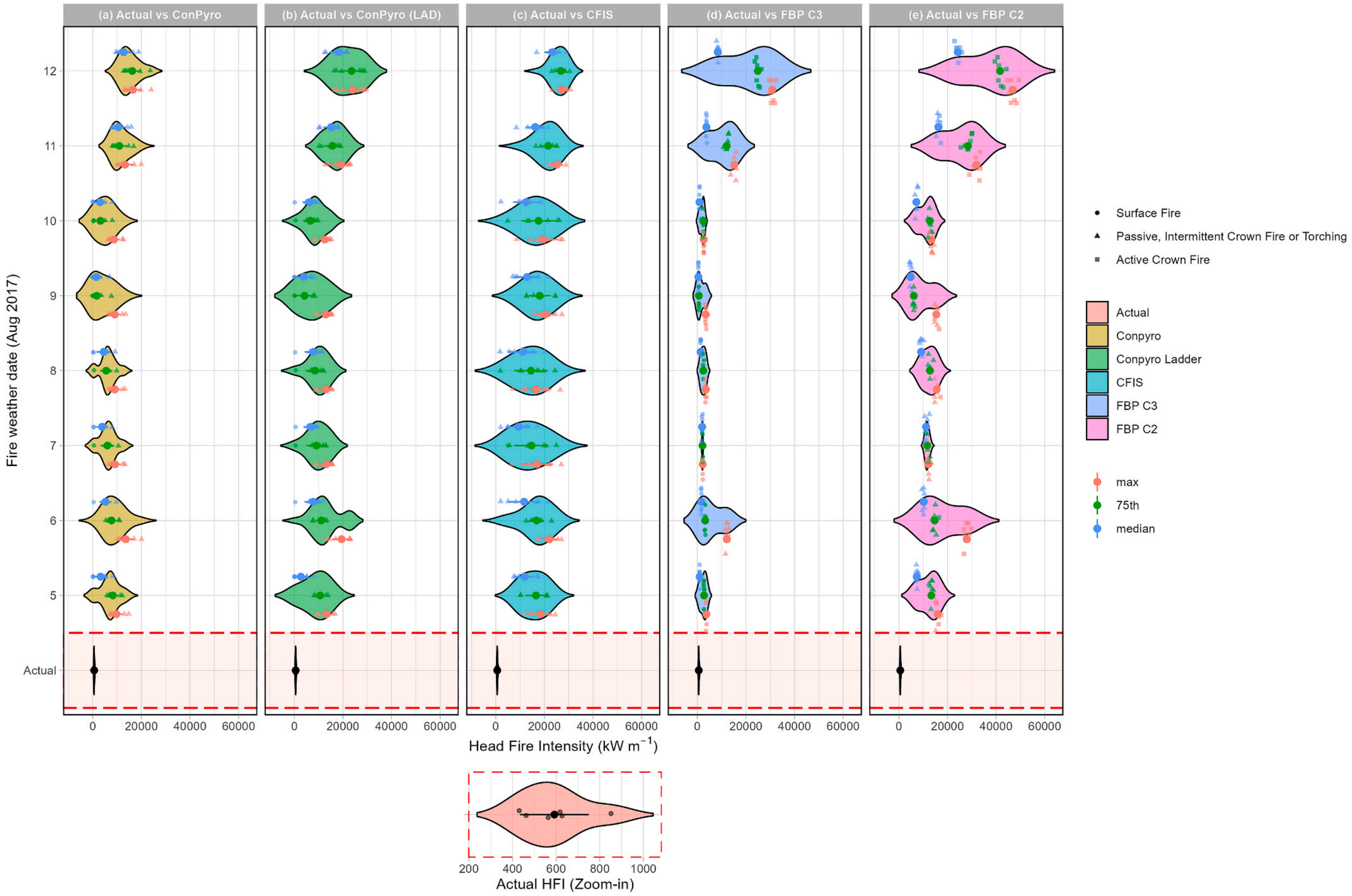

Fig. 4. Distribution of modelled HFI at three wind percentiles derived from ConPyro, CFIS and FBP in the treated stand vs. reconstructed HFI. Each violin plot shows the range and distribution of HFI prediction from all plots, with individual plot contribution shown as jitter and their 95% confidence intervals. The left-most group shows the HFI range and distribution pattern for reconstructed HFI in the treated-burned stand. (a) ConPyro predictions vs reconstructed HFI, (b) ConPyro with ladder fuel function predictions vs reconstructed HFI, (c) CFIS predictions vs reconstructed HFI, (d) CFIS with ladder fuel function predictions vs reconstructed HFI, (e) FBP predictions vs reconstructed HFI. The sub-plot shows a zoomed view of the range and distribution of reconstructed HFI.

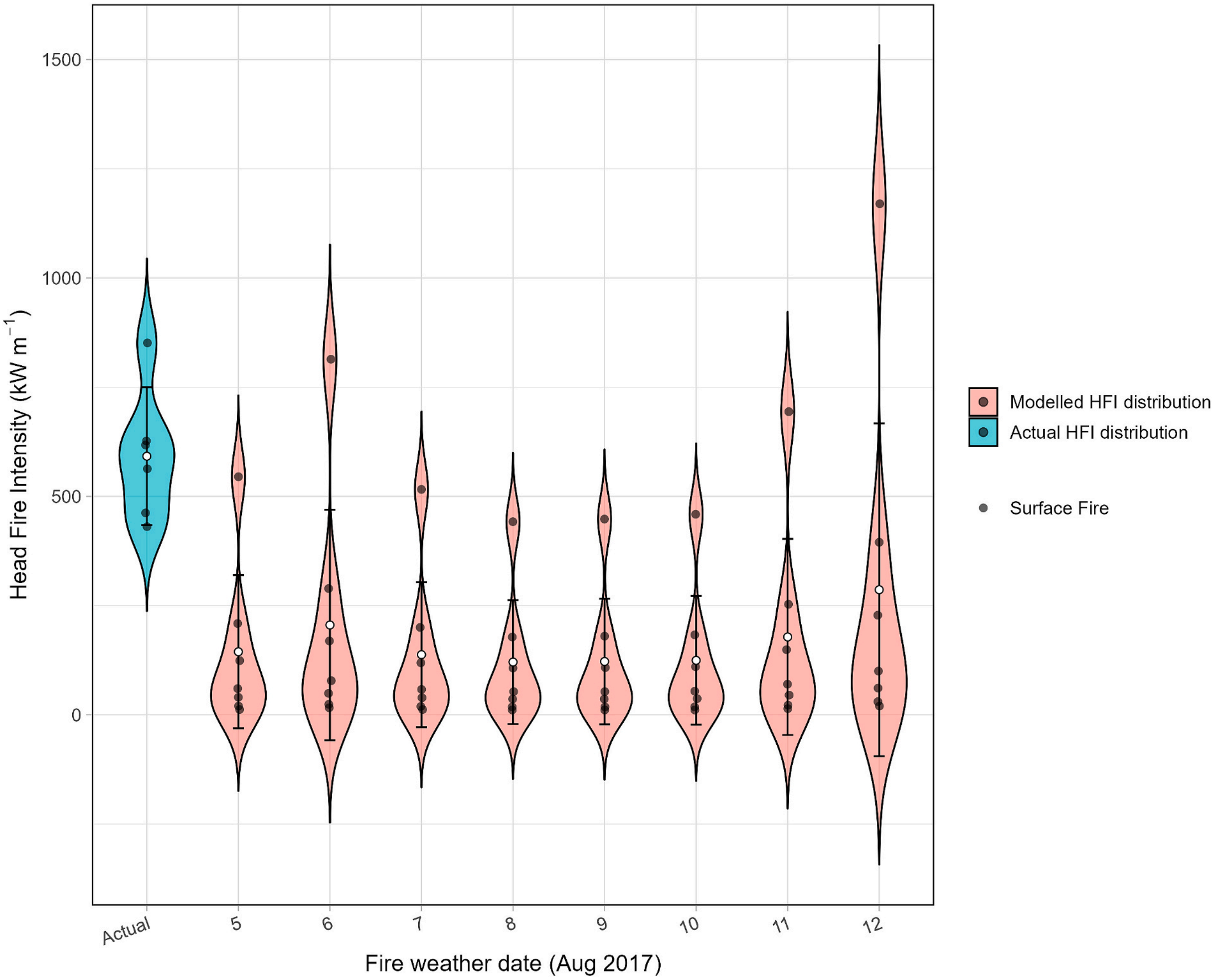

Fig. 5. Distribution of modelled head fire intensity in the treated stand from BehavePlus. HFI for each date was modelled at maximum wind speed of each day. The left-most group shows the HFI range and distribution pattern for reconstructed HFI in the treated-burned stand. Each violin shows the HFI range and distribution pattern of prediction on a different date, with exact prediction from each plot shown as jitter along with their 95% confidence interval.

regression results showed mixed significance, with 12 of 24 indicating significant differences ($P < 0.05$), primarily at the $\tau = 0.50$ quantile. Most comparisons at the 0.75 and 0.9 quantiles were not significant on several days, indicating closer agreement at the upper end of the reconstructed distribution. BehavePlus predictions exhibited little response to day-to-day variation in fire-weather conditions, with relatively stable HFI values across the modelled period (Fig. 5).

4. Discussion

The outcomes of this study are discussed separately for untreated and treated stands. This distinction is necessary because the evaluated fire behaviour models were primarily developed and calibrated using data from natural forest stands characterized by relatively continuous canopy structures. Consequently, model predictions for untreated stands provide a measure of predictive accuracy, whereas results for treated stands primarily reflect model applicability rather than accuracy.

4.1. Untreated stand modelling as a model accuracy assessment

Both untreated-burned and untreated-unburned stands in this study were characterized by a similar, continuous, and relatively uniform canopy layer. This structure closely resembles conditions represented in the training datasets used to develop the evaluated fire behaviour models, thereby supporting their applicability in these environments. As a result, comparisons between model-predicted HFI for untreated-unburned stands and reconstructed HFI untreated-burned stands constitute an assessment of model accuracy under appropriate conditions.

Results presented in Fig. 3 indicate that none of the evaluated fire behaviour models precisely predicted the mean or full range of reconstructed HFI for the untreated stand. Conpyro without the ladder fuel function consistently underestimated HFI in the upper quantiles at all wind-speed percentiles. At median wind speed, underestimation was also evident for ConPyro with ladder fuels and for FBP using the C3 fuel type (Table S1). BehavePlus exhibited the strongest underestimation bias, producing several orders of magnitude lower HFI predictions than Canadian models. FBP predictions fluctuated widely across wind-speed percentiles and alternated between under- and overprediction, limiting confidence in its predictive reliability. These findings are consistent with previous evaluations reporting low overall predictive accuracy and a prediction bias in many operational fire behaviour models (Cruz and Alexander, 2013; Cruz et al. 2010).

Model performance varied notably at the 75th and maximum wind percentiles. Incorporating the ladder fuel function into ConPyro resulted in an upward shift in predicted HFI values and improved agreement with reconstructed fire intensity distributions. This improvement was reflected in lower MAQD values and closer alignment with observed HFI across most quantiles. This improvement is observed because the ladder fuel function accounts for the influence of small-diameter dead saplings and midstory trees, which can facilitate vertical fire spread and reduce effective canopy base heights (Stocks 1987; Cruz et al., 2004; Perrakis and Thompson, 2025). Additionally, the multi-layer canopy representation enabled ConPyro to more accurately reflect crown involvement in understory and midstory fuel layers, consistent with the observed stand structure comprising an intermittent hybrid spruce layer beneath a mixed overstory of live and dead lodgepole pine.

CFIS also generated predicted HFI ranges that overlapped reconstructed values, although with a stronger overestimation bias in the upper distribution tail. Despite this bias, CFIS achieved the second-lowest overall MAQD values among the evaluated models. Cruz and Alexander (2013) proposed that a ± 35% error interval represents a reasonable benchmark for evaluating contemporary fire behaviour models. Within this criterion, HFI predictions produced by ConPyro with ladder fuels, and CFIS at the 75th and maximum wind percentiles fall within the acceptable accuracy limits, suggesting that these models could provide useful guidance for management decisions in similar untreated stands with continuous canopy structure.

In contrast, FBP produced a wide range of HFI predictions that were consistently overestimated and exhibited no variance among plots; this reflects the rigid nature of the FBP fuel types, wherein varying stand inputs produce identical outputs (Forestry Canada Fire Danger Group, 1992; LaCarte, 2024). BehavePlus, in contrast, produced tightly constrained HFI estimates that were well below reconstructed values, consistent with previous studies documenting strong underprediction of fire spread rate and intensity relative to Canadian models (Drury, 2019). Collectively, these results indicate that ConPyro with ladder fuels and CFIS outperformed FBP and BehavePlus in predicting the magnitude and distribution of HFI in untreated lodgepole pine stands.

4.2. Reconstructed and modelled HFI in treated stand

Comparisons between reconstructed HFI and model predictions in treated stands should not be interpreted as measures of model accuracy, as all evaluated models were developed using data from natural stands with continuous canopy cover. The treated stand examined in this study exhibited a patchy and discontinuous canopy structure that falls outside the intended application domain of these models. Model results for treated stands are therefore discussed in terms of applicability rather than predictive validity.

In treated retention patches, ConPyro (simple canopy), ConPyro (with ladder fuels), and CFIS consistently produced HFI estimates that substantially exceeded reconstructed values. Given that these models demonstrated an ability to approximate reconstructed HFI distributions in untreated stands at the same study site, they were expected to yield similar predictions in treated retention patches, which retained broadly comparable stand structure. The persistent overestimation observed here suggests that key processes contributing to reduced fire intensity in treated stands were not adequately represented. Spatial heterogeneity in stand structure has long been recognized as an important determinant of disturbance severity (Hessburg et al., 1994), yet this structural complexity is not explicitly represented in most operational fire behaviour models. The observed overprediction of HFI in treated stands therefore highlights the limitations of current model formulations when applied to forests with spatially discontinuous canopy structure, where processes such as spotting, acceleration, and surface-crown fire transitions are poorly represented (see Sec. 4.3, below).

FBP predictions for treated stands generally indicated reduced HFI relative to untreated stands, suggesting some representation of treatment effects (Fig. 4 d-e). However, predicted HFI increased sharply under extreme fire-weather conditions on 11 and 12 August, indicating strong sensitivity to wind speed and limiting the utility of the model for isolating treatment effects. BehavePlus consistently underestimated reconstructed HFI in treated retention patches and showed little distinction between treated and untreated stands, reflecting low sensitivity to structural change (Fig. 5). This finding aligns with previous research reporting minimal differences in BehavePlus predictions between treated and untreated conditions (Fernandes, 2009).

4.3. Implication on modelling treatment effect

Reconstructed HFI values in the treated-burned stand were substantially lower than those from the untreated-burned stand (Fig. 3–5), consistent with a broad body of empirical and modelling research demonstrating that thinning and related fuel treatments reduce fire intensity and crowning potential by disrupting fuel continuity (Collins et al., 2013; Loudermilk et al., 2014; Cruz et al. 2017; Volkova et al. 2017). In the irregular shelterwood system examined here, canopy openings likely caused crown fires advancing out of retention patches to transition to surface fire within openings, thereby reducing head fire intensity before spread into adjacent retention patches. This interpretation aligns with observations from wildfire-affected managed forests and supports the effectiveness of spatially heterogeneous treatments in moderating fire behaviour.

In contrast, modelled HFI from ConPyro (simple), ConPyro (with ladder fuels), and CFIS did not capture this reduction in fire intensity within the treated stand (Fig. 3, 4a-c). At the 75th and maximum wind-speed percentiles, these models produced HFI ranges for treated stands that were similar to, or greater than, those predicted for untreated stands. Under extreme fire-weather conditions on 11 and 12 August, predicted HFI substantially exceeded reconstructed values and, in some cases, approached or surpassed predictions for untreated stands. Incorporation of the ladder fuel function further increased both the magnitude and variability of predicted HFI for ConPyro, resulting in greater overestimation from reconstructed values (Fig. 3, 4a-b). This response differs from previous modelling studies reporting reduced predicted fire intensity for treatments such as strip cuts (Marshall et al., 2020), shrub group removal (Loudermilk et al. 2014), and pruning (Cruz et al. 2017). Notably, Marshall et al. (2020) identified irregular cluster cuts—-structurally comparable to the irregular shelterwood treatment examined here—as producing the greatest simulated reductions in HFI.

The discrepancy between reconstructed and modelled results likely reflects a combination of treatment structure, fuel sampling methodology, and model applicability. To avoid confounding effects associated with averaging fuel characteristics across highly heterogeneous retention patches and openings, model input data for treated stands were derived exclusively from retention patches. While this approach preserved internal consistency among plots, it likely over-represented fuel loads relative to conditions encountered by a fire spreading across a heterogeneous treatment mosaic. In addition, retention patches may have experienced elevated surface and woody fuel loading due to accumulation of harvest debris and downed material from adjacent openings. Consequently, modelled HFI in treated stands likely reflects in-patch fire behaviour rather than integrated fire behaviour across the treated stand as a whole. These results reinforce the limitations of applying stand-level fire behaviour models to treatments that deliberately create spatially discontinuous canopy structures within residual stands.

4.4. Limitation and future research

All fire behaviour models have inherent limitations that influence their predictive performance and applicability. For BehavePlus, the well-documented underprediction of crown fire behaviour associated with the coupled Rothermel–Van Wagner formulations remains a central limitation (Scott and Reinhardt, 2001; Cruz and Alexander 2010). When combined with surface fire spread models that tend to underestimate rate of spread, this limitation contributes to persistently low predictions of fire intensity relative to Canadian models (Cruz and Alexander 2010; Drury 2019).

The Canadian Forest Fire Behaviour Prediction (FBP) System relies primarily on empirical rate-of-spread and fuel consumption functions developed from a limited set of experimental fires (Forestry Canada Fire Danger Group 1992; Wotton et al. 2009). As a result, predicted fire behaviour is highly sensitive to fuel type selection. Neither the C2 nor C3 fuel types were developed to represent partially insect-killed lodgepole pine stands typical of central interior BC, limiting their suitability for the conditions examined here. This mismatch likely contributed to the strong sensitivity of predicted HFI to wind speed and the large variability observed under extreme fire-weather conditions.

CFIS provides a relatively simple and operationally accessible framework for predicting crown fire initiation and spread, drawing on empirically derived models for crown fire occurrence and crown rate of spread (Cruz et al. 2004; Cruz et al., 2005). While these models are widely used, limitations remain in key input variables, particularly estimated fine fuel moisture and the use of categorical surface fuel consumption classes. These inputs have not been validated for use in sub-boreal forests of BC and may reduce the model's ability to discriminate among fuel environments with subtle but meaningful differences.

ConPyro demonstrated improved performance relative to other models in untreated stands, particularly when ladder fuels were incorporated; however, substantial uncertainties remain regarding ladder fuel consumption, canopy fuel configuration, and the representation of three-dimensional fuel continuity (Perrakis et al. 2020; Perrakis et al. 2023; Perrakis and Thompson 2025). Accurately measuring, parameterizing, and calibrating these fuel layers continues to pose significant challenges and will require targeted, field-based studies. In addition, processes such as ember lofting, deep charring of standing dead wood, and feedbacks between fire spread and discontinuous canopy openings are not explicitly represented in current operational models and may contribute to discrepancies between observed and simulated fire behaviour (Talucci and Krawchuk 2019; Jasper Fire Documentation, Reconstruction, and Analysis Task Team 2025).

Aside from the limitations of the models tested, we acknowledge that HFI is less commonly used than ROS as a measure of fire behaviour. However, HFI was considered the more appropriate indicator for this study for two main reasons. First, there was no real-time record of fire spread during the wildfire event, and ROS was therefore not directly observed or documented at the time of burning. Because this study is comparative in nature, using ROS as the primary metric would leave no observed benchmark against which model outputs could be evaluated. Second, although ROS could theoretically be derived from the reconstructed HFI by rearranging Byram's equation, this would still yield a rough estimate rather than a directly observed value. In our case, such a reconstructed ROS would remain fully dependent on the reconstructed HFI, and would introduce further uncertainty without providing any independent information. For these reasons, HFI was considered the more suitable fire behaviour indicator for the present study.

The case-study nature of this research necessarily limits inference beyond the specific stand structure and wildfire event examined. Future research should extend evaluation and calibration of fire behaviour models across a wider range of forest types, fuel treatments, and climatic conditions. In particular, the development of modelling approaches that explicitly represent spatial heterogeneity and canopy discontinuity will be essential for improving fire behaviour predictions in both natural forests and managed stands subject to contemporary silvicultural treatments.

5. Conclusion

This study evaluated the accuracy and applicability of four widely used fire behaviour models—FBP, CFIS, ConPyro, and BehavePlus—using field-based evidence from a wildfire that burned through lodgepole pine stands treated with an irregular shelterwood silvicultural system in interior British Columbia. In untreated stands characterized by continuous canopy structure, ConPyro and CFIS produced the closest agreement with reconstructed head fire intensity, particularly at higher wind-speed percentiles. Incorporating ladder fuels in ConPyro improved representation of crown fire involvement and resulted in the highest overall prediction accuracy among the evaluated models. In contrast, FBP produced highly variable predictions that were strongly sensitive to fuel type selection and wind speed, while BehavePlus consistently underestimated fire intensity. In treated stands with discontinuous canopy structure, however, none of the tested models produced predictions comparable to field evidence, suggesting poor model applicability. While ConPyro and CFIS provide useful guidance for untreated stands with continuous canopy in interior BC, their application to treated stands requires caution. Future model development should focus on explicitly incorporating stand structural complexity and spatial discontinuity to improve predictions of fire behaviour in both natural and managed forest landscapes.

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Declaration of AI-assisted technologies

During the preparation of this work the author(s) used ChatGPT in order to improve writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Mingrui Liu: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Gregory Greene:** Writing – original draft, Writing – review & editing, Supervision, Software, Methodology, Investigation. **Daniel D.B. Perrakis:** Writing – original draft, Writing – review & editing, Software, Methodology. **Dominik Roeser:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2026.103789.

Data availability

All data supporting the findings of this study will be deposited in OSF (doi:10.17605/OSF.IO/ZBPGR) and made publicly available upon publication. The repository record will include the dataset, README, and analysis code.

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