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FIRE SCIENCE AND MANAGEMENT (M ALEXANDER, SECTION EDITOR)

Global Synthesis of Quantification of Fire Behaviour Characteristics in Forests and Shrublands: Recent Progress

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Abstract

Purpose of Review The behaviour of wildland fires, namely their free spreading nature, destructive energy fluxes and hazardous environment, make it a phenomenon difficult to study. Field experimental studies and occasional wildfire observations underpin our understanding of fire behaviour. We aim to present a global synthesis of field-based studies in forest and shrublands fuel types published since 2003 with a focus on the most commonly measured fire behaviour attributes, namely rate of fire spread, ignition and spread sustainability, flame characteristics, fuel consumption and spotting behaviour.

Recent Findings We present a synthesis of measured fire behaviour data collected in field experiments and wildfire environments encompassing the last two decades. We discuss the effect of a lack of standardised experimental methodologies in field studies, which has inhibited our quantitative understanding of the physical drivers of fire behaviour. The application of new fire environment and behaviour measuring sensors and methods offer opportunities for more comprehensive descriptions of fire spread characteristics, particularly when applied to wildfire events, to better capture scale dependent phenomena that do not occur at smaller experimental scales.

Summary Fire behaviour data collected in field experiments and wildfires form the foundation of our quantitative understanding of fire dynamics. These data are used in the development and evaluation of predictive models with operational and scientific applications. We provide a broad synthesis of existing field-based studies in forest and shrubland ecosystems and discuss their limitations and needs for future research.

Keywords Experimental fires · Rate of fire spread · Fire spread sustainability · Flame characteristics · Fuel consumption · Spotting · Integrated fire-behaviour measurements · Fuel types

Introduction

A wildland fire has three basic characteristics, namely it spreads, it consumes fuel, and it produces heat energy in a visible flaming combustion reaction. Understanding of wildland fire behaviour [1], namely its response to changes in environmental conditions and links with fire effects, is necessary to better mitigate and manage a fire's impacts in regard to ecological and human values. Nonetheless, wildland fire is a poorly understood and complex phenomenon incorporating chemical, physical, and biological processes. The mechanisms influencing how a fire consumes biomass and propagates occur over a broad range of spatial and temporal scales, from millimetres to kilometres and from seconds to hours, respectively [2], and are obviously difficult to measure and model comprehensively.

The collection of data from fires burning in wildlands fuels, be it from wildfires or, more commonly, smaller

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field-scale experimental fires and operational prescribed burns, is necessary to improve our understanding of wildland fire dynamics and development of models with operational and research applications. Modelling of wildland fire behaviour can be seen as following two apparently contrasting approaches: (1) a so-called 'empirical' approach where statistical methods are applied to observational fire behaviour data to develop simple analytical descriptions of certain fire attributes such as rate of fire spread or flame size; or (2) a 'physical', or process-based approach, where the developed models are based on fundamental relations derived from first principles of one or more processes assumed to drive fire behaviour, such as mass and energy conservation, combustion chemistry, fluid flow and heat transfer processes [3, 4].

The empirical approach has enabled the development of robust predictive models [5–7] that have been used to support a broad range of fire management decision making, from prescribed fire planning [8, 9], to supporting wildfire suppression and the issuing of public warnings [10]. However, these models are generally unable to give insight into the complex processes driving fire propagation, such as how different fuel layers affect overall wildfire propagation or the relative roles of radiative versus convective heating. The empirical modelling approach produces models that are specific to a particular fire behaviour attribute for a specific set of conditions (e.g. fuel type, prevailing weather, etc.). In contrast, physical models are able to provide a more holistic description of the fire behaviour processes and aim to provide insight into the mechanisms determining what a fire does and how it does it (e.g [4, 11, 12]). However, the physical modelling approach has not received widespread acceptance in operational applications, due to a number of factors including computational and data requirements, organizational support and training, and an overall lack of practitioners' exposure to these models. The recent development of simplified or reduced process-based models that can run in near real-time have shown promise for operational use [13, 14].These tools are still early in their development and not widely supported or used outside of research applications.

The empirical and physical modelling approaches should not be viewed as mutually exclusive, and often successful modelling combines elements of both the empirical and physical approaches (e.g [15]). ; see reviews in [16–18] and a timeless discussion on the "two solitudes" by C. E. Van Wagner [19].

The use of purposely designed outdoor experimental fire behaviour studies or opportunistic study of appropriate operational prescribed burns have been the main sources of fire behaviour data aimed at measuring fire characteristics and impacts in as realistic a setting as possible. This approach can be traced to the earliest scientific research of wildland fire behaviour [1]. Independently of the fire source type, experimental versus prescribed burns, these types of fires have been used to collect data for a multitude of purposes, reflecting the often multi-disciplinary nature of modern wildland fire research. Ignition likelihood [20, 21], flame front propagation [22, 23], flame characteristics ([24], energy fluxes [25–27], smoke emissions [28, 29], firebrand transport ([30, 31], fuel consumption [32, 33], instrument calibration [34–36], testing personal protection equipment [37], quantifying the effectiveness of fire retardants [38] and fuel treatments [39], and measuring direct and indirect fire effects [40–42], are just a few examples of research subjects studied under field conditions.

In this synthesis we present and discuss studies published in the past two decades that focus on the collection of field-scale fire behaviour data, and associated model development and evaluation, with a focus on forest and shrubland vegetation. In presenting published work, we separate experiments into two main approaches. One approach emphasizes data collection across a large number of fires over a range of weather conditions [23, 43, 44]. This approach has been the primary approach utilised for much of the empirical, management oriented, fire behaviour research in countries such as Australia and Canada. A second approach aimed at intensive measurement of fundamental properties of a flame front and the surrounding environment (e.g [29]). , typically relies on a small, but highly instrumented, number of experiments [45, 46] and aim to link data collection methods to the development, calibration and evaluation of a range of fire behaviour and effects models. We review these types of studies in the first two sections of this article. We also provide a summary of global fire behaviour data collected and published. Finally, we discuss some pertinent aspects related to experimental data and the role of wildfire data in improving our understanding of scale dependent wildfire behaviour phenomena.

Field-scale Fire Behaviour Observations and Models

Field-based fire behaviour research in experimental and wildfires form the basis of much of our knowledge of wildland fire dynamics [1, 18, 47, 48]. This research has focused on a number of fire behaviour characteristics, namely the ignition and sustainability of fire propagation, fire acceleration up to pseudo steady state, fire front movement, i.e., rate of spread, and features of the flaming zone, i.e., energy release, residence time, flame size and angle, fuel consumption and other phenomena such as the occurrence of secondary fires, i.e., spot fires. The focus on these variables stems from their relationship with fire effects and relevance in supporting fire management activities such as suppression and issuing of warnings.

In reviewing published work, we constrained our analysis to studies published over the last two decades that contained at least 10 independent fire experiments or observations, ensuring a level of replication from which reliable understanding of fire dynamics can be extracted. For earlier reviews see [18, 48–51].

Rate of Fire Spread

The rate of fire spread, or the speed a flame front moves, is the most widely studied fire behaviour quantity [47]. Its importance stems from the free spreading nature of the flame front in a wildfire, where knowledge of how a wildfire grows across the landscape is needed to plan suppression actions and ensure the safety of fire fighters and the general population. This speed also determines how much of the available fine fuel is involved in combustion per unit time, which then determines important energy release metrics, such as the widely used Byram's fireline intensity [52, 53], and a large array of subsequent fire effects [39].

We identified 48 studies focusing on collecting field-based rate of fire spread data (Table 1). The overarching objective of these studies was to understand the effect of environmental variables on the forward spread rate of the fire, with a few studies describing also flank and back-fire propagation. Methods to measure the movement of the flaming front varied, from ocular estimates by observers on the ground [e.g. 30, 54] to the use of visual and infra-red (IR) imagery from aircraft [55] or unmanned aerial vehicles [56]. Most studies considered solely time of one-dimensional propagation between two known points. Detailed measurements incorporating the shape of the fire and the detailed variation of rate of spread in time and space are seldom conducted or described in experimental burn programs with a substantial number of fire replicates.

It is worth noting the developing trend of studies that publish their collected experimental and wildfire data [e.g. 7, 59, 60], which then have then been used by other researchers in developing new models [e.g. 61], calibrating existing ones [e.g. 13, 62] or adjusting inputs [e.g. 63,64], or testing novel modelling approaches, such as genetic algorithm optimisation [e.g. 64], neural networks [e.g. 65] and other machine learning methods [66]. Such published data have also been used to independently evaluate new and existing empirical and process-based models [e.g. 61, 67,68].

Ignition Success and Fire Spread Sustainability

The understanding of the conditions that allow (1) an ignition source to successfully ignite a fuel bed and (2) a flame front to self-sustain its propagation in a fuel layer (e.g., duff, litter, canopy) are rather important, but poorly understood and seldom studied, processes. Ignition of fuels and flame propagation can be simply idealised as a balance between the energy released by combustion and transported to the unburned fuel and the energy necessary to ignite these fuels. If the energy impinging in the unburned fuels is not enough to ignite them and maintain a self-sustained process, the flame front will self-extinguish. The understanding of fire dynamics under marginal burning states [69] and knowledge of the required environmental conditions that allow for sustained flame front propagation are necessary to determine fire spread in less than optimum burning conditions, such as those associated with high fuel moisture contents during prescribed burn operations or during overnight lulls in wildfire activity [7]. This is also relevant when considering fire propagation in horizontally or vertically discontinuous fuel complexes such as found in semi-arid environments [70-72] or where vertical fire propagation, such as crowning, occurs [73]. Here we consider the sustainability of a spreading flame front, either as a surface fire, i.e., consuming litter and understorey vegetation, or a crown fire, i.e., involving surface and crown fuels [74].

Often the distinction between ignition success and fire spread sustainability is not clearly defined. We found a total of 13 field-based studies (Table 2) investigating the threshold conditions defining ignition success and surface fire spread sustainability (also known as go/ no-go conditions), with the data distributed mostly in shrublands ($n = 5$ studies) and forests ($n = 8$). The different ignition types (i.e., point vs. line), sizes of the experiment, and vegetation characteristics, meant that the definition of fire spread sustainability varied significantly between studies. Most of the studies in forests relied on smaller scale experiments, with sustained flame front propagation declared if an experiment spread over a short period of time, typically less than 5 min [75, 76] or a distance (varying between 1.5 m [77, 78] and 30 m [75]. Experiments in shrublands tended be larger (fire runs 10–20 m) to integrate some of the natural variability in fuel structure and continuity [79, 80]. In discontinuous semi-arid shrub fuels, Cruz et al. [81] defined sustainable spread to occur after a 50 m wide ignition line spread over 75 m after realising that some fires were self-extinguishing after spreading 35–50 m. The higher the fuel discontinuity, the larger the plot size requirements to ensure propagation encompasses the heterogeneous nature of fuel and the results are not biased towards sustained fire propagation.

Modelling fire spread sustainability has mostly relied on multiple logistic regression analysis [76, 77] and its variations [e.g. 79], although other statistical approaches, such as structural equation models [78], regression trees [82], and machine learning [83] have also been used. Dead fuel moisture content, or its primary drivers air temperature and relative humidity, has been often identified as the main controller of fire spread sustainability. Wind speed and a fuel structure descriptor have also been found in some studies as significant variables. Lack of wind and fuel variability in the datasets often precluded the identification of these variables as significant in the process being analysed [e.g.79, 80].

Table 1 Objectives, data, and findings of fire spread rate (R) studies. Publications listed in fuel type (forests, shrublands) and chronological order

Study and objective	Data	Findings	Data published
Forests			
Stocks et al. [22]; experimental crown fire behaviour project on boreal forest; aimed at collect data to parameterize and evaluate existing models.	10 experiments on plots up to 2.2 ha in size. R range: 15–70 m min^{-1}. Further data given in [138] and [25].	Comprehensive dataset assembled on established crown fire propagation. Crown fire data only. Data used to evaluate empirical models and the parameterization of Albini [99] physical model (see [95]) and later other numerical models [e.g.186].	Yes
Taylor et al. [138]; to assess temporal and spatial variation in R in relation to wind speed in boreal forests, Canada.	Subset of [22] data. R range: 18–67 m min^{-1}.	Explore different methods to infer R and its relationship with wind measurement location. Explores R variability from experimental average.	Yes
Bilgili et al. [100]; to develop practical fire behaviour prediction guides for immature Calabrian pine (*Pinus brutia*) forests.	Twenty-two experiments in plots of variable size up to 15 × 21 m. R range: 1.7–13.8 m min^{-1}. See also Table 4	Simple linear regression analysis used to develop models of rate of fire spread covering low to moderate burning conditions. Most significant variables were wind speed and canopy base height.	Yes
Cruz et al. [205]; to develop crown fire spread rate models for conifer forests.	Used data from historical burn projects in Canada; data used given in [206]. R range: 7.54–51.4 m min^{-1}.	Models for active and passive crown fire R identified wind speed, dead fuel moisture and canopy bulk density as main explanatory variables. Models evaluated against independent data.	No
Alexander and Cruz [188]; to evaluate the predictive capacity of Cruz et al. [205] model using a large independent dataset from wildfire case studies.	Collation of 57 wildfire observations from case studies undertaken in Canada and USA. R range: 10.7–107 m min^{-1}.	Cruz et al. [205] model evaluated against an independent dataset and benchmark fit statistics for model adequacy proposed. Sources of uncertainty and what constitutes reasonable error discussed. Model fit compared with other models.	Yes
Kucuk et al. [207]; to study the development of point ignition fires in black pine (*Pinus nigra*) forests.	Twenty-five line and point ignition experiments in 3 × 1 m plots (3 m run). Rates of fire spread varied between 0.1–1.2 m min^{-1}.	Models of rate of fire spread developed from small scale experimental line and point ignition fires ($n = 52$) covering low to moderate burning conditions. Contains analysis of fire growth from point ignition. Most significant variables were wind speed and dead fuel moisture content.	Yes
Gould et al. [30]; describe a broad study on fire behaviour in dry eucalypt forest (Jarrah, *E. marginata*) under dry summer conditions in southern Australia.	Ninety-eight experiments in plots 200 × 200 m over a range of fuel ages; R range: 0.9–23 m min^{-1}.	Describes the experimental methods in detail, and the modelling of dead fuel moisture content, wind speed within the forest stands, rate of fire spread, flame characteristics, spotting behaviour and fuel consumption. Interim model for rate of fire spread described (see updated version in [60]. Wind speed, fine fuel moisture content and three fuel characteristics were found to best explain fire spread rate. See [208] and [23] for further description of experimental data.	No
Tanskanen et al. [75]; to document fire behaviour characteristics in southern boreal *Pinus sylvestris* and *Picea abies* forests in Finland.	Data from experimental fires ($n = 35$) in 30 × 30 m plots. R range: 0.1–3.4 m min^{-1}.	Descriptive analysis of R data. See also Table 2.	Yes

Table 1 (continued)

Study and objective	Data	Findings	Data published
Cruz and Fernandes [63]; to test a backtracking calibration procedure to develop fuel models for the Rothermel [15] model.	Data from experimental fires in maritime pine (*Pinus pinaster*) forest in Portugal from [209]. A total of 42 fire runs were used, with R range: 0.25–6 m min^{-1}.	Two different fuel models to be used with Rothermel [15] surface fire spread model were developed. Study discusses advantages of parameterization method over building fuel models from fuel structural characteristics. Results are contrasted with other existing models.	No
Fernandes et al. [54]; to increase the understanding of surface fire behaviour in *Pinus pinaster* forests under mild burning conditions.	Data from 94 experimental fires in 10 × 15 m plots; R range: 0.1–13.9 m min^{-1}.	Rate of forward fire spread explained as a function of surface wind speed, terrain slope, moisture content of fine dead surface fuel, and fuel height. Back-fire spread rate was explained by fuel moisture content and cover of understorey vegetation. Models are implemented in prescribed burn guides.	No
Wiriya and Kaitpraneet [169]; to investigate relationships between fire behaviour and environmental variables in dry deciduous tropical forests, Thailand.	Study considered twenty-one experiments (each 200 × 200 m in size) with a point ignition at the centre of the plot. R range: 0.6–3.9 m min^{-1}.	Rates of forward spread of point ignition fires under mid burning conditions were found to be correlated with wind speed, fuel bed depth and live fuel moisture content.	Yes
Knapp et al. [210]; to evaluate fire behaviour and effects in masticated fuels in *Pinus ponderosa* stands burned under prescription condition, USA.	Data from eight 0.04 ha plots burned under prescribed burns conditions. Striped ignition. R for head and backing fire regions.	Unclear how striped ignition influenced observed rate of fire spread. Data used to evaluate fuel models for the Rothermel [15] surface fire spread model.	Yes
Kilinc et al. [211]; to evaluate the performance of several R models in eucalypt forests of southern Australia.	Data from 186 wildfires; R range: 1.7–260 m min^{-1}.	Describe evaluation statistics for several R models used in Australia. Identifies most accurate model as Cheney et al. [60]. Discusses sensitivity of models to fuel moisture content and discusses its impact in model results.	No
Kucuk et al. [150]; to investigate surface fire spread in young immature calabrian pine (*Pinus brutia*) plantations, Turkey.	Set of 35 experimental fires (variable ignition line length, from 1 to 5 m) in pine litter fuels; R range: 0.3–3.8 m min^{-1}.	Linear regression modelling used to describe rate of spread as a function of wind speed and quantity of dead fine fuels. Variable ignition line length possibly influencing results as this variable was correlated with wind speed and fuel load.	Yes
Cheney et al. [60]; to develop an operationally applicable fire spread model for dry eucalypt forest of southern Australia.	Data from 98 experimental fires [30] used for model development; R varying between 0.9 and 23 m min^{-1}. Model evaluation against independent experimental ($n = 16$) and wildfire ($n = 25$) data. R range: 2.5–175 m min^{-1}.	Model for forward spread rate of wildfires under summer burning conditions based on 10-m open wind speed, fine dead fuel moisture content, surface and near surface fuel visual hazard score [208] and near surface fuel layer height. Model currently used operationally in Australia. See also [30] and [23] for methods and data details.	Partially
Perrakis et al. [144]; to model the spread rate of wildfires in lodgepole pine (*Pinus contorta*) stands impacted by mountain pine beetle, British Columbia, Canada.	Data from experimental ($n = 2$) and wildfire ($n = 14$) case studies used. R range: 2.6–66 m min^{-1}.	Model for fire spread following the Canadian FBP system [5] modelling approach, with the Initial Spread Index (ISI; [212] being the independent variable. Onset of crown fire activity also identified as a function of ISI. Observations and predictions contrasted with other FBP system fire spread models.	Yes

Table 1 (continued)

Study and objective	Data	Findings	Data published
Fernandes [62]; to derive a simple multiplier to allow the use of Fernandes et al. [54] model to wildfire situations.	Data from 5 published wildfire case studies; R range: 3–21.8 m min^{-1}.	Evaluation of Fernandes et al. [54] model shown it to under predict the R of fires burning under conditions more severe than the ones used for its development. Calibration of the model is proposed to allow its application to wildfires burning in dry and windy conditions.	Yes
Alves et al. [57]; to study fire behaviour under prescribed burning conditions in *Eucalyptus urograndis* plantations, Brazil	Fifteen experiments in 3 × 20 m plots under nil wind conditions across a range of long-term dryness conditions. R range: 0.3–0.9 m min^{-1}.	Descriptive analysis of data.	Yes
McRae et al. [55]; to investigate fire growth/acceleration from a point source ignition in semi-mature jack pine (*Pinus banksiana*), Canada.	Twenty-three point source and small line fire experiments conducted under mild conditions in 40 × 40 m plots at the Sharpsand Creek experimental study area (see also [88, 140]). R range: 0.1–0.9 m min^{-1}.	Slow moving fires did not show any fire acceleration pattern.	Yes
Kucuk et al. [151]; to model the rate of surface fire spread in even aged Anatolian black pine (*Pinus nigra*) in Turkey.	Experimental fires ($n = 25$) with ignition line lengths varying between 1 (3 m run) and 5 m (5 m run); R range: 0.5–6.9 m min^{-1}.	Multiple linear regression approach used to model rate of fire spread. Several combinations of explanatory variables used. Wind and fuel load were significant variables, but fuel moisture and ignitions line length (both correlated) were not related to R.	No
Cruz and Alexander [213]; to develop a simple relationship to quickly estimate a wildfire's spread rate simply from the open wind speed.	Data from wildfire datasets ($n = 118$) in shrublands [7], Australian eucalypt [60] and North American conifer [188] forests. R range: 4.8–175 m min^{-1}.	A simple approximation of forward wildfire rate of spread was proposed as 10% of wind speed; this approximation is only applicable for dry (dead fuel moisture < 7%) and windy (10-m open wind > 30 km h^{-1}) conditions.	No
Fernandes et al. [181]; to provide an overall worldwide picture of fire behaviour characteristics, patterns and drivers.	Data from published studies including about 6000 fire behaviour entries.	Study describing BONFIRE project objectives and methodology. Some exploratory data analysis conducted, namely examination of data by country, climate, biome and fuel complex categories.	No
Cruz et al. [214]; to evaluate the predictive ability of the 10% rule of thumb [213] against independent wildfire datasets.	Wildfire R dataset from [211] ($n = 61$) and [181] ($n = 57$); R range: 9.1–208 m min^{-1}.	The rule of thumb was shown to work well for heightened fire danger conditions, with errors comparable to other model evaluation studies based on wildfire data. The results showed that the conditions where the rule of thumb worked best were more restricted than originally thought.	No
Storey et al. [194]; to explore the use of a Bayesian approach to modelling R for Australian eucalypt forests.	Data ($n = 223$) from wildfire observations; R range: 4.8–153 m min^{-1}.	Bayesian modelling approach used to describe wildfire R. Best model included wind speed, relative humidity and soil moisture (weak effect). A model based on the Australian Forest Fire Danger Index [160] is also proposed.	No

Table 1 (continued)

Study and objective	Data	Findings	Data published
Cruz et al. [61]; to develop an operationally applicable fire spread model for dry eucalypt forest of southern Australia.	Data from 87 experimental fires [30]and wildfires [60] used for model development; R varying between 0.03 and 175 m min^{-1}. Model evaluation against independent experimental fires ($n = 16$; [60]) and wildfire runs ($n = 90$; [211, 215]) data. R range: 0.8–133 m min^{-1}.	Model for the spread rate of wildfires under a broad range of burning conditions takes into consideration different propagation states (low, moderate to high, very high intensity). Variables found to influence fire propagation were 10-m open wind speed and a wind reduction factor, fine dead fuel moisture content, surface fuel load and understorey shrub fuel height, drought factor and slope steepness. Model evaluated against independent data and error characterised along a spectrum of burning conditions.	No
Cardil et al. [56]; to assess the performance of fire spread models implemented in a spatial wildfire simulator against wildfire data.	Data from wildfire observations ($n = 1853$); observed R up to 48 m min^{-1}; unknown number of fires in forest fuel types.	Evaluation of the Wildfire Analyst Enterprise (WFA-e) modelling framework against wildfire observations. Fuel and weather input data originated from machine learning methods and Weather Research and Forecast model, respectively. General description of error given by broad fuel types. Identification of fuel types with higher error.	No
Kucuk and Sevinc [66]; to investigate the application of machine learning methods for the prediction of surface R in *Pinus nigra* stands in Turkey.	Data from 33 small scale experiments (1 × 1, 3, and 5 m). No details on data distribution provided. See [151] for methods.	Neural network and decision tree models used to model rate of fire spread. Weight of explanatory variables found to be dependent on the modelling approach. Artificial Neural Network approach superior to Decision Tree method.	No
Shrublands			
Bilgili and Saglam [59]; to gather fire behaviour data in maquis fuels of southwestern Turkey.	Experimental fires ($n = 25$) in plots 20 (W) x 30 (L) m. R range: 0.8–8.9 m min^{-1}.	Study found wind speed and several fuel variables, namely vegetation cover, fuel load and vegetation height, to be significantly correlated with R. Linear regression models combining these variables developed for R.	Yes
Davies [58]; to describe the relationships between fire behaviour and fuel and weather conditions in *Calluna vulgaris* moorlands, north-east Scotland.	Experimental burns ($n = 14$) in plots 15 (W) x 20 (L) m. R range: 0.0–12.6 m min^{-1}.	Relationships between R and wind speed for different fuel structures is discussed. Model for R based on fuel height and wind speed proposed and evaluated against independent data.	Yes
Vega et al. [171]; to collect fire behaviour data aimed at better modelling fire propagation in Iberian Peninsula shrublands.	Fire spread observations ($n = 79$) from several field campaigns, extending over 16 experimental areas. R range: 1.4–27.1 m min^{-1}.	Effect of environmental variables quantified through a modelling approach. Wind speed and slope found to be significant variables controlling fire spread rate.	No
Ascoli et al. [216]; to understand the effect of fuel load and R on fire suppressibility in shrub fuels, Italy.	Data from 22 experimental fires with variable size (25 to 50 ignition line lengths). R range: 0.4–17.9 m min^{-1}.	Descriptive analysis of R.	Yes
Legg et al. [217]; understand key factors controlling variation in fire behaviour in *Calluna vulgaris* moorlands, north-east Scotland.	Nine experimental fires in 20 × 20 m plots, extending [58] dataset. R range: 0.0–12.6 m min^{-1}.	Analysis of most influential factors driving fire propagation in this fuel type. Model of rate of fire spread under prescribed burning conditions developed with data from this study plus [58], with wind speed, fuel height and live fuel moisture being most relevant variables. Model evaluated against independent data.	Yes

Table 1 (continued)

Study and objective	Data	Findings	Data published
Saglam et al. [103]; to increase the understanding of the effect of slope on fire propagation in shrublands, Turkey.	Experimental fires ($n = 17$) in 15×25 m plots over a range of slope steepness up to 15%. R range: 0.6–8.4 m min^{-1}.	Linear regression analysis used to quantify fire dynamics, with the most influential variables found being wind speed, slope, and live fuel moisture content.	Yes
Saglam et al. [174]; determine fire behaviour characteristics based on varying weather conditions in tall maquis in Mediterranean environment, Turkey.	Experimental fires ($n = 18$) in 20×30 m plots. R range: 0.4–7.4 m min^{-1}.	Models based on regression analysis were proposed for R, with wind speed, vegetation cover and live fuel moisture chosen as independent variables.	Yes
Davies et al. [175]; to understand fire behaviour in *Calluna vulgaris* dominated heathlands, Scotland.	Experimental fires ($n = 27$) in 15–20 (W) x 20 (L) m plots; R range: 0.5–12.6 m min^{-1}.	Application of redundancy analysis to investigate most influential variables. R largely determined by wind speed. Best subsets regression used to generate models of R, with wind speed, fuel height, canopy fuel moisture content and fuel heterogeneity (index).	No
Cruz et al. [81]; to develop models describing the effect of fuel and weather on fire behaviour in South Australia semi-arid eucalypt shrublands, Australia.	Experimental fires ($n = 67$) ranging in size from 100×100 to 250×250 m; R range 3–55 m min^{-1}.	Surface and crown fire spread models develop as a function of wind speed, fine fuel moisture content and fuel structural variables. Various models developed to allow different fuel input options. Model turned into a prescribed burning guide.	No
Fontaine et al. [80]; to examine the effect of fuel age and weather variables on fire behaviour in Proteaceae-dominated kwongan shrublands of Western Australia.	Experimental fires ($n = 35$) at three distinct sites with variable plot size (median size ~ 0.5 ha). R range 4.8–94.2 m min^{-1}.	Limited evidence for an effect of fuel age or fire weather on rates of spread. Data used to evaluate BehavePlus 5.0 system [218] predictions.	Yes
Cruz et al. [71]; to develop models for R in semi-arid eucalypt shrublands, Australia.	Used experimental and prescribed burn data ($n = 61$) from [89]and [81]; R range: 4 to 55 m min^{-1}.	Developed operational models for surface and crown fire R. R explained by wind speed, fine dead fuel moisture, and fuel height and cover metrics. Model evaluation against experimental and wildfire case study data ($n = 26$). Models currently used operationally in Australia.	Yes
Vacchiano et al. [219]; to calibrate and use FVS [220] in southern European heathlands, Italy.	Data from 40 wind driven experimental fires (25–50 m ignition line length). R range: 1–26 m min^{-1}.	Fire behaviour data used for fuel model calibration. Data accessible as training data in [221].	Yes
Rossa and Fernandes[68]; to develop generic models of R under no wind conditions; evaluate against field experiments.	Used R data from low intensity fires in different fuel types, namely eucalypt plantation ($n = 16$; [222]); rainforest ($n = 36$; [77, 164]) and pine forest [54] for model evaluation; R range: 0.1–1.5 m min^{-1}.	Two different R models based on physical principles developed; one model based on dead fuel moisture content and fuel bed height; second model adds surface area to mass ratio as a predictor. Models evaluated against field data.	No
Anderson et al. [7]; to develop a generic rate of fire spread model applicable to a wide range of shrubland types around the world.	Used experimental and prescribed burn R data ($n = 79$) from multiple sources around the world. Model evaluated against data from prescribed burns ($n = 67$) and wildfires ($n = 32$). R range: 1–100 m min^{-1}.	Two models developed with wind speed and dead fuel moisture content, plus either shrub height or fuel layer bulk density as explanatory variables. Analysis on the effect of ignition line length on R, and discussion on slope effect. Model currently used operationally in Australia.	Yes
Ascoli et al. [64]; to apply genetic algorithm optimisation to develop custom fuel models for the Rothermel surface fire spread model [15].	Used experimental R data from difference sources ([223, 224]: $n = 10$; [225]: $n = 14$; [226]: $n = 14$; [219]: $n = 40$) for calibration and validation; R range: 1–26 m min^{-1}.	Successfully developed more accurate fuel models than previous approaches. Discussion on advantages of genetic algorithm optimisation approaches to fuel modelling.	Yes

Table 1 (continued)

Study and objective	Data	Findings	Data published
Rossa and Fernandes [227]; to develop a simple empirical model for estimating the effect of wind speed on R.	Data from forest ($n = 46$; [54]) and shrubland ($n = 44$; [171, 228–230]) fuel types used for model testing. R range: 0.2 to 20.7 m min^{-1}.	Model for wind aided R developed. Agreement against field data considered good by authors.	No
Pepin and Wotton [231]; to carry out and document a series of experimental fires in Nova Scotia shrublands, Canada.	Experimental fires ($n = 15$) burned over two distinct seasons (spring and summer) in 15 × 25 m plots. R range: 1.5–13.9 m min^{-1}.	Noise in data noted to affect results. No wind speed (measured 0.8 km away from fire location) and fuel moisture effect on R. Data used to contrast with nine existing models.	Yes
Wadhwani et al. [65]; to apply neural network (NN) techniques to develop a R model for shrubland fuel types.	Used a subset of R data compiled by [7]; No details of which particular data was used.	Preliminary results show potential of NN to model R.	No
Chatelon et al. [13]; to parameterize and evaluate a physical-based model for R in shrublands fuels.	R data ($n = 25$) from [59] for model parameterization and [7], $n = 109$, for model evaluation.	Simplified physical model aimed at operational applications showed good agreement with independent data. Model parameterization framework able to be extended to other fuel types.	No
Minsavage-Davis and Davis [232]; to evaluate different R models for shrubland fuel types.	R data from Scottish Calluna-dominated shrublands [175], $n = 27$, used for model evaluation.	Present and discuss the different models fit against the data.	Yes

Only a few experimental field studies were found that dealt with the likelihood of crown fire activity. For conifer forests, the studies identified [84, 85] were based on existing data from historical experimental burn programs [e.g. 5, 86,87, 88]. Combining data from different published studies gives a modelling dataset with a wider range of fuel and weather conditions that better quantifies the effect of environmental variables on fire processes. The onset of crowning in Australian semi-arid eucalypt shrublands has also been modelled by combining distinct datasets [81, 83, 89].

Flame Zone Characteristics

Knowledge of flame characteristics in free spreading fires is needed to understand and estimate impacts of fire on ecosystem components [90], suppression difficulty [91], radiation exposure [92, 93], and to drive the development of more complex models of fire propagation [94, 95]. Flame dimensions and geometry, such as flame height, angle, and depth, are the most commonly observed flame front characteristics in fire behaviour experiments [96]. We identified 17 studies measuring and modelling flame dimensions in experimental fires (Table 3). These studies, seven in shrubland fuel types and seven in eucalypt and pine forests, covered a broad range of fireline intensities and flame sizes, ranging from low intensity back-fires with flame heights of 0.1 m to high intensity intermittent crowning fires with flame heights up to 14 m. It is worth noting that flame dimensions are often visually estimated during experiments or from photographic or video recordings [96]. The transient nature of flame characteristics and the lack of defined and accepted measuring methods leads to high uncertainty in the measurements [97, 98] and lack of consistency when comparing studies relating flame dimensions with other fire behaviour quantities and effects [48]. Often the characterization of flame dimensions is not the main aim of the study, with these characteristics being a secondary data type that is often obtained opportunistically. Its modelling is also often just a minor element in a publication with little detail provided on methods and analysis [e.g. 7, 54,60].

Detailed measurement of other flame properties, such as its temperature as it varies in time and space, radiative properties, and fluid flow velocities are seldom measured in experimental burn programs with a substantial number of fire replicates. This is primarily due to the difficulties in obtaining such measurements in free-spreading fires and the onerous nature of such measurements. Detailed measurements of flame properties tend to be conducted in multidisciplinary data measurement campaigns aimed at collecting fundamental energy transfer data [90]. Of note, in two of the

Table 2 Objectives, data, and findings of fire ignition, spread sustainability and type of fire (surface vs. crown) studies

Study and objective	Data	Findings	Data published
Cruz et al.[84]; to develop model of crown fire occurrence in boreal forest using Canadian Forest Fire Weather Index (FWI) system components [212].	Data ($n = 63$) from studies carried out in Canada encompassing several different forest stand types and a wide range of fuel complex structures. Data is subset of FBP System dataset [5]. Data given in [206].	Developed different models describing the likelihood of crown fire occurrence in Canada boreal forest from canopy base height, 10-m open wind speed, and four components of the Canadian FWI System [212]: Fine Fuel Moisture Code, Drought Code, Initial Spread Index and Buildup Index. Models evaluated against independent data [22, 233].	No
Cruz et al. [85]; to develop model of crown fire occurrence based on environmental variables.	Data ($n = 71$) from outdoor experimental fires in Canada, Australia and Portugal. Data given in [206].	Logistic regression analysis used to develop model for the likelihood of crown fire occurrence based on 10-m open wind speed, fuel strata gap, estimated moisture content of fine dead fuels, surface fuel consumption. Models evaluated against independent data [22, 233].	No
Tanskanen et al. [75]; to document fire behaviour characteristics in southern boreal *Pinus sylvestris* and *Picea abies* forests in Finland.	Data from experimental fires ($n = 35$) in 30 × 30 m plots. Burn cover and fire spread sustainability estimated.	Model of burn success stands based Canadian FWI System [212] outputs and stand type.	Yes
Beverly and Wotton [20]; to investigate likelihood of sustained flaming in boreal forest surface fuels.	Analysis of historical data on small scale experimental fires ($n = 1207$). Ignition relied on use of household wooden match in contact with surface fuels. Fires classified as self-extinguished or self-sustained.	Models for probability of sustained flaming propagation developed for 10 combinations of fuel type and surface fuel from the Canadian FWI System [212] components, dead fuel moisture content and relative humidity. Fine dead fuel moisture content found to be the most influential variable determining sustained flaming.	
Fernandes et al. [76]; to identify the environmental variables determining self-sustained propagation of a line fire in maritime pine stands of Portugal; to develop predictive model.	Data from 265 assessments of fire spread sustainability, with 57 corresponding to non-sustained propagation. Fire sizes ranged from fire sustainability trials with 2 m wide line fires to larger fire behaviour experiments in 10–15 m wide plots.	Dead fuel moisture content, understorey weather measurements and fuel complex descriptors had significant influence on the probability of self-sustained fire spread. Logistic regression analysis used to model likelihood of fire spread, incorporating the effect of dead fuel moisture content, fire spread direction (forward or backward), fuel type and ambient temperature.	No
Cruz et al. [81]; general study aimed to develop models describing the effect of fuel and weather on fire behaviour in South Australia semi-arid eucalypt shrublands, Australia.	Data ($n = 67$) from experimental fires and operational prescribed burns with linear ignition lines varying between 75 to 125 m. A total of 34 fires failed to spread.	A number of models with different fuel structure variables developed for the prediction of fire spread sustainability and crown fire occurrence. Dead fuel moisture content and wind speed were the common variables across all models.	No

Table 2 (continued)

Study and objective	Data	Findings	Data published
Anderson and Anderson [79]; to determine the variables that affected ignition and sustained fire spread in gorse (*Ulex europaeus*) stands in New Zealand; to develop predictive model.	Data from point ignition ($n=37$) and spread sustainability ($n=19$) experiments. Plots varied between 7–15 m (W) x 8–24 m (L).	Probability of ignition and sustained spread modelled through ordinal logistic regression from the elevated dead fine fuel moisture content alone. Small number of fires, with note that "Further investigation of the effect of wind speed and additional data collection from a greater range of wind and fuel moisture conditions are necessary" [79].	No
Davies and Legg [170]; to determine the role of weather and fuel moisture in governing ignition and sustained combustion of fires in *Calluna vulgaris* shrublands, Scotland.	Data ($n=20$) from point and line ignitions experiments in 2×2 m plots.	Best model for ignition and sustained propagation had a fuel moisture factor comprising the moisture content of the lower canopy and moss/litter layer. Results also identify the patchy behaviour of going fires, likely indicating that larger fires would be necessary for conclusive results.	Yes
Fontaine et al. [80]; to examine the effect of fuel age and weather variables on fire behaviour on Proteaceae-dominated kwongan shrublands of Western Australia	Experimental fires ($n=35$) at three distinct sites with variable plot size (median size ~ 0.5 ha). 10 fires failed to propagate.	Time since fire was a strong predictor of fire propagation. Little support in the data for the effect of fire weather variables in determining fire sustainability "within the range of experimental conditions". Shrubland type also not related to likelihood of fire propagation.	Yes
Cruz et al. [71]; to develop fire behaviour prediction models for semi-arid eucalypt shrublands, Australia.	Experimental and prescribed burn data ($n=61$) from [89] and [81]; variable ignition line lengths. Wildfire and operational prescribed burn data used for model validation.	Likelihood of sustained fire spread and crown fire propagation modelled using logistic regression analysis. Fire spread sustainability was primarily a function of litter fuel moisture content with wind speed having a secondary but still significant effect. The continuity of fine fuels close to ground level was also significant. Onset of crowning determined by wind speed.	Yes
McRae et al. [55]; to present and discuss findings from a series of experimental fires in the Canadian boreal forest.	Data from 21 experimental fires in Canadian boreal forest. Data pertain to experiments with different ignition types and sizes.	Descriptive study with data presented and discussed within the context of the uncertainties in fire behaviour, effect of ignition type and fire growth.	
Filho et al. [77]; to predict the probability of fire spread and to improve understanding of fire propagation in rainforest fuels, Brazil.	Data from 72 point-ignition experimental fires at 18 different sites, under no wind conditions. Plots were circular with a 1.5 m radius.	Models of ignition success developed from logistic regression analysis incorporating the effect of litter fuel moisture content and litter height.	Yes
Cawson and Duff [21]; identify the key fuel-bed attributes influencing ignitability under marginal fire weather conditions in eucalypt forests, Australia.	Data from 45 independent ignitions in five different operational prescribed burns.	Probability of ignition modelled through logistic regression analysis. Surface fine-fuel moisture content and overall fuel hazard (i.e. fuel arrangement) were the strongest predictors of ignition likelihood.	No

Table 2 (continued)

Study and objective	Data	Findings	Data published
Newberry et al. [78]; to understand how vegetation structure controls fire ignition and propagation in savanna-forest in Cerrado vegetation, Brazil.	Data from 102 experimental fires in 3 × 3 m plots over a range of savanna-forest structures.	Logistic regression and structural equation models used to investigate main drivers of sustained propagation. Results indicate basal area and weather variables such as relative humidity, air temperature, and vapour pressure deficit, as main influencing variables.	No
Cawson et al. [82]; to understand the drivers of litter ignitability from flaming firebrands in wet and damp eucalypt forests, Australia.	Data from 1590 ignition attempts across two fire seasons and six sites. Ignition with flaming firebrands. The ignition was sustained if the fire continued burning for 5 min or burnt 0.5 m from the point of ignition.	Exploration of the effect of a large number of variables. Regression tree analysis identified the moisture content of litter and near surface fuels, plus in-forest vapor pressure deficit as main variables determining ignition and sustained ignition.	No
Perrakis et al. [234]; to understand and model the probability of crown fire occurrence in Canadian conifer forests.	Data ($n = 113$) from experimental fires carried out in Canada between 1960 and 2019. Base data is refined from data used by [85].	Alternative inputs tested. Best models describe crown fire probability as a function of open wind speed, fuel strata gap, litter moisture content and surface fuel consumption. Models predicted correctly 92% of the data used in model development.	No
Khanmohammadi et al. [83]; to test artificial intelligence methods in classifying fire sustainability and crown fire occurrence.	Data from [71] comprising experimental and prescribed burn data [81, 89] for model fitting and wildfire and other prescribed burn data for model evaluation.	Several machine-learning (ML) classifier approaches tested. Support Vector Machine was determined as the optimum ML classifier based on model overall accuracy against an independent evaluation dataset.	No

Table 3 Objectives, data, and findings of flame zone characteristics studies

Study and objective	Data	Findings	Data published
Butler et al. [25]; to collect spatially and temporally resolved measurement of energy intensity and air temperatures in full-scale crown fires, Northwest Territories, Canada	Radiant heat fluxes and flame radiometric temperatures from multiple measurement locations in 6 experimental crown fires [22].	Descriptive analysis. Peak flame temperatures exceeded 1330 °C, and maximum radiant energy fluxes reached 290 kW m^{-2}. Maximum values occurred in the upper third of the forest stand where the bulk of crown fuel is. Measured flame temperatures showed variation with vertical height in the canopy.	No
Taylor et al. [138]; to collect flame front residence time, time-temperature curves and flame temperature profiles in boreal forests, Northwest Territories, Canada.	Data on flame front temperature and residence time in nine9 experimental fires [22].	Descriptive study of flame temperature dynamics with height on high intensity fires. Peak flame temperatures up to 1300 °C; residence times ranged up to 94 s. Contrast between video and thermocouple data used to derive flame residence time.	No
Davies [58]; to describe the relationships between fire behaviour and fuel and weather conditions in *Calluna vulgaris* moorlands, north-east Scotland.	Fourteen experimental burns in plots 15 m (W) x 20 m (L). Flame height range: 0.4–1.9 m.	Models of flame length based on fireline intensity or a Canopy Density Index applicable to prescribed burning conditions.	Yes
Anderson et al. [49]; to gather information on flame characteristics from recent laboratory and field experiments, and fit models that have been proposed in the literature.	Published and unpublished data from six different sources, only one being field experiments [209].	Exploratory analysis of a number of flame length, height and angle models against the data. Found different trends based on laboratory (varying with source) and field sources.	No
Legg et al. [217]; to understand key factors controlling variation in fire behaviour in *Calluna vulgaris* moorlands, north-east Scotland.	Nine experimental fires in 20 × 20 m plots, extending [58] dataset. Flame length range: 0.4–1.9 m.	Model of flame length based on fireline intensity under prescribed burning conditions. Provided contrast between photographic flame length and field estimated flame length.	Yes
Gould et al. [30]; to study fire behaviour in dry eucalypt forest (Jarrah, *E. marginata*) under dry summer conditions in southern Australia.	Ninety-eight experiments in plots 200 × 200 m over a range of fuel ages. Flame height range: 0.3 to 14 m; residence time range: 46–87 s.	Descriptive analysis of residence times and flame temperatures (see Wotton et al. [24] below). Modelling of flame height using R and shrub fuel height as explanatory variables. See also [23] for data description and [60] for follow up modelling.	No
Fernandes et al. [54]; to better understand surface fire behaviour in *Pinus pinaster* forests under mild weather.	Data from 186 measurements of head and back fire flame dimensions in 10 × 15 m experimental fires. Flame height and length range: 0.05–4.2 m	Presented different modelling options of flame height and lengths. Different models for back and forward propagation. Models implemented in prescribed burn guides [235].	No
Knapp et al. [210]; to evaluate fire behaviour and effects in masticated fuels in *Pinus ponderosa* stands burned under prescription condition, USA.	Data from eight 0.04 ha plots burned under prescribed burns conditions. Striped ignition pattern. Flame lengths for head and backing fire regions. Flame length up to 0.9 m.	Flame length data compared with loading of burned unit. Flame data for heading and backing fires used to evaluate performance of BehavePlus 5.0 predictions for different fuel models.	Yes
Cruz et al. [81]; general study aimed to develop models describing the effect of fuel and weather on fire behaviour in South Australia semi-arid eucalypt shrublands, Australia.	Measurements of flame height, length and angle in 33 experimental fires (100 × 100 to 250 × 250 m plots). Residence time measurements in 20 experimental fires. Flame height range: 0.3–6 m; flame length range: 0.3–12 m.	Exploratory analysis of relationships between environmental variables, fire behaviour and flame characteristics. Evaluation of different flame height, length and residence time models against the collected data.	No

Table 3 (continued)

Study and objective	Data	Findings	Data published
Cruz et al. [27]; to measure the radiosity and gas temperatures of flames spreading in shrubland vegetation, Portugal.	Measurements ($n = 11$) of flame radiosity and temperatures in experimental fires (variable plot size, with an average plot width of 55 m). Peak radiosity range: 10–170 kW m^{-2}; peak flame temperature range: 600–1300 °C.	Descriptive analysis of flame radiosity and temperature profiles.	Yes
Wotton et al. [24]; to characterise the time–temperature structure of flames in dry eucalypt forests, Australia.	Experimental fires ($n = 42$) instrumented with multiple 3-m tall thermocouple towers. Residence time range: 21 to 62 s; maximum flame temperature range: 700–1100 °C.	Analysis of residence time and vertical flame temperature profiles. Model of flame temperature along its height developed.	No
Cheney et al. [60]; to develop an operationally applicable flame height model for dry eucalypt forest of southern Australia.	Ninety-eight experimental fires in plots 200 × 200 m over a range of fuel ages. Flame height range: 0.3 to 14 m;	Modelling of flame height using R and shrub fuel height as explanatory variables, plus a bias correction factor. Model noted to have application bounds of $R < 1.5$ km h^{-1} and shrub height < 2 m. See also [30] and [23] for data description.	No
Cruz et al. [71]; to develop a model for flame height in semi-arid eucalypt shrublands, Australia.	Data from 17 experimental fires [81, 89]. Flame height range: 1–8 m.	Flame height modelled as a function of fireline intensity.	Yes
Frankman et al. [146]; to collect time-resolved convective and radiative heat fluxes in natural and prescribed wildland fires, USA	Data from 12 prescribed burns; Flame height range: 0.4–30 m. Radiative flux range: 24–300 kW m^{-2}; Peak convective flux 13–140 kW m^{-2}.	Convective heating at the sensor surface varied from 15% to values exceeding the radiative flux. Detailed measurements of convective and radiative heating rates in wildland fires are presented.	No
Sparks et al. [236]; to relate fire radiative flux with tree response; provides fuel consumption data in prescribed burns, USA.	Data from 9 prescribed burns. Provides data on flame length, residence time and smouldering time	Analysis does not focus on flame characteristics, but data is provided. No analysis of fire behaviour variables was conducted.	Yes
Munoz et al. [237]; to model the probability of occurrence of a certain flame geometry for specific fuel structures.	Field scale flame dimension data from multiple published sources present in Fernandes et al. [181] BONFIRE database.	Approach attempts to model the likelihood of a certain fire dimension occurring directly from environmental variables. Flame length and angle in different fuel types modelled as a function of fine fuel load, moisture content and wind speed.	No
Rossa et al. [238]; to develop a generic flame length – fireline intensity relationship in forest and shrublands.	Data on flame length in forest ($n = 406$) and shrubland ($n = 207$) fuel types compiled in the Fernandes et al. [181] BONFIRE database.	A generic flame length-fireline intensity relationships for surface fires is proposed. Results are contrasted with other existent models and variability presented. Usefulness of a generic model to estimate fireline intensity from flame length is discussed.	No

largest scale field experiment projects ever conducted in forest fuel types, Project Vesta in Australia [30] and the International Crown Fire Modelling Experiment in (ICFME) in northwestern Canada [44], detailed measurements of flame temperatures, residence times [24] and radiant emissive power [25] were obtained on a large number of experiments. Some of this fundamental data were then used to parameterize a physics-based fire spread model [95, 99].

Fuel Consumption

Fuel consumption, i.e., the amount (on a dry basis) of dead and live biomass consumed by fire is an important fire behaviour property for the determination of fire characteristics such as the energy and CO_2 release, smoke production, and fire effects on ecosystem components. Fuel consumed can be divided by combustion type: flaming or glowing — although it should be recognised that it is virtually impossible to measure biomass consumption in flaming combustion in isolation in a field setting. Fuel consumption is often given as absolute biomass consumed [100] or a proportion of pre-fire fuels consumed [101, 102]. Often field studies assume that all fine fuels are consumed in flaming combustion [52], with remaining fuels, such as duff fuel layers and coarse woody debris, consumed in glowing combustion behind the flame front. Studies on fuel consumption on shrubland fuels (Table 4) generally consider consumption of all fine live and dead fuels) within the shrub canopy [59, 103].

Studies in forest systems (Table 4) often consider fuel consumption by layer and fuel type, e.g., litter, duff, coarse woody debris class [104, 105]. A substantial number of studies focused on the consumption of coarse woody debris, the largest carbon pool impacted by fires [32, 33, 104, 106–109]. See Kreye et al. [110] for a review of field studies in masticated fuels. The consumption of fuels in distinct layers/types is largely influenced by the moisture contents of the different fuel layers/elements. Studies also found a direct effect of fire intensity [102] or remotely sensed fire severity metrics on the proportion of fuel consumed [111]. Given the dominant effect of moisture content in the fuel consumption process, development of predictive models requires datasets covering a broad range of fuel and landscape dryness conditions [101, 104, 112]. See [51, 104] and [113] for reviews of pre-2010 experimental and modelling work.

Spotting

Spotting, the process by which lofted firebrands transported downwind of the flame zone ignite new fires outside the active fire perimeter, is a complex process influencing landscape wildfire growth. Considering the transport and density of firebrands (i.e. not the generation of firebrands and ignition of new spot fires), the study of these processes and influential variables is constrained in an experimental field setting by the size of the experiment, the energy released and the associated plume development. Experimental fire studies have aimed to characterise short-range spotting distances and densities and have been restricted to one [31, 46, 114] or a few experiments [23, 30] (Table 5); see also the review by Wadhwani et al. [115]. Given the scale dependence of some of the processes determining spotting densities and distances, as influenced by plume dimensions and the integrated energy release over a broad area, it is unlikely that experimental fires will be able to adequately replicate the processes driving medium to long-range spot fire dynamics in wildfires.

Studies based on thermal infrared imagery collected in wildfires [116] have provided new insights into the phenomena, in particular identifying patterns of spot fire distribution and the fire and environmental factors dominating spotting behaviour in north-western US conifer [117] and southern Australia eucalypt forests [118, 119]. Wind speed, fire size and growth trend, and topography were identified as key drivers of long-distance spotting.

Integrated Data Collection Campaigns

To support a more robust understanding of the physical and biological processes that drive fire behaviour and its linkage to fire effects and smoke, scientists are increasingly designing and carrying out interdisciplinary measurement campaigns [29, 44, 120]. The most salient feature of these campaigns is that data collection is designed to assist in multiple scientific endeavours, including evaluating various predictive models, testing specific a priori hypotheses, and providing opportunities to explore data and generate new hypotheses. Such campaigns are exemplified by the ICFME [44], RxCADRE [29], the New Zealand Scion/USDA Missoula Fire Laboratory experiments [121, 122], FASMEE [120], along with a host of other experiments [e.g. 13, 123, 124, 125].

Though data collection during integrated measurement campaigns varies depending upon the specific goals, they typically involve making measurements of fundamental environmental (wildland fuels and vegetation, atmospheric conditions, terrain, fuel moisture content), fluid dynamics and heat transfer, fire behaviour and effects attributes [29]. In these experiments, collection of environmental and fire behaviour data aims to be detailed, with high spatial and temporal resolution. This results in large data sets comprising multiple linked data products that are collected for each experiment, irrespectively of their size.

Vegetation and fuel data collection on recent integrated measurement campaigns are linking traditional field data with terrestrial and airborne based remote sensing tools,

Table 4 Objectives, data, and findings of fuel consumption studies

Study and objective	Data	Findings	Data published
Bilgili and Saglam [59]; to gather fire behaviour data in maquis fuels of southwestern Turkey.	Experimental fires ($n = 25$) in plots 20 m (W) x 30 m (L). Fuel consumption range: 1.3–3.2 kg m^{-2}. See also Table 1.	Study found fuel consumption to be strongly correlated with fuel structural variables, such as fine fuel quantity, woody fuel quantity and vegetation height, and live and dead fuel moisture content. Linear regression models combining these variables were developed.	Yes
Bilgili et al. [100]; to develop practical fire behaviour prediction guides for immature Calabrian pine (*Pinus brutia*) forests.	Experimental fires ($n = 22$) in plots of variable size up to 15 × 21 m. Fuel consumption range: 2.0–3.0 kg m^{-2}. See also Table 1.	Models of fuel consumption developed from experimental burn data covering low to moderate burning conditions. Fuel consumption was modelled as a function of surface and canopy fuel load.	Yes
Saglam et al. [103]; to increase the understanding of the effect of slope on fire propagation in shrublands, Turkey.	Experimental fires ($n = 17$) in 15 × 25 m plots over a range of slope steepness up to 15%. Fuel consumption range: 1.0–2.3 kg m^{-2}. See also Table 1.	Fuel consumption related to fuel structure variables such as fuel load, cover, and height. Moisture content variables not significant in explaining fuel consumption. Fuel consumption modelled from fine fuel load.	Yes
Bradley et al. [239]; to examine fuel consumption in masticated fuels burned in mixed shrub woodlands, USA	Prescribed burns in ten treatment blocks with measurements conducted at 1 m^{-2} subplot level.	All fires were backing with respect to slope and/or wind. Fuel consumption results given in graphical form.	No
Gould et al.[30]; describes a broad study on fire behaviour in dry eucalypt forest (Jarrah, *E. marginata*) under dry summer conditions in southern Australia.	Experimental fires ($n = 98$) in plots 200 × 200 m over a range of fuel ages; Bark fuel consumption given in mm. See also Table 1.	Report describes methods used to quantify bark fuel consumption. Bark consumption was found to be related primarily to pre-fire bark quantity. Results varied with site. See [23] for further analysis of fuel consumption.	No
de Groot et al. [240]; to develop models of surface fuel consumption for Canadian boreal forest fuel types.	Database comprising experimental fires associated with the Canadian Forest Fire Behaviour Prediction (FBP) System [5]. ($n = 59$) coupled with wildfire sampling ($n = 69$). Range of fuel consumption only given graphically.	Fuel consumption in wildfires estimated from paired unburned sites. Models of forest floor fuel consumption given as function of multiple possible inputs, with best explanatory variables being fuel layer bulk density, Drought Code and Build up Index. Forest floor fuel load also found as a significant variable.	No
Hollis et al. [32]; to evaluate the predictive capacity of woody fuel consumption models in southern Australian eucalypt forests.	Experimental and operational prescribed burn data ($n = 39$) from distinct studies. Consumption of litter, fine and coarse woody fuels. Woody fuel consumption up to 52 kg m^{-2}.	Woody fuel consumption was found to be highly variable between sites. Relationships between woody fuel consumption and the primary model drivers were weak.	Yes
Knapp et al.[210]; to evaluate fuel consumption in masticated fuelbed in *Pinus ponderosa* stands burned under prescription condition, USA.	Data from eight 0.04 ha plots burned under prescribed burns conditions. Overall fuel consumption varied between 1.6 and 3.7 kg m^{-2}.	Brief presentation of average absolute and percent fuel consumption by site.	No
Hollis et al. [102]; to investigate the relationship between fireline intensity and woody fuel consumption across different Australian eucalypt forests.	Data from experimental, operational prescribed burns and wildfires published in different studies. Woody fuel consumption range: 0.8–52 kg m^{-2}.	Generalised linear models describing woody fuel consumption as a function of fireline intensity developed. One restricted to prescribed fire environments and the other across the full range of fireline intensities.	No

Table 4 (continued)

Study and objective	Data	Findings	Data published
Hollis et al. [104]; to develop an empirically based model for woody fuel consumption by fires in Australian southern eucalypt forest fires	Data from experimental fires, operational prescribed burn and wildfires published in different studies. Woody fuel consumption range: 0.8–52 kg m^{-2}.	Variation in fire behaviour found to potentially have a greater impact on woody fuel consumption, than does variation in fuel characteristics. Developed models for woody fuel consumption by size class and stage of the combustion process. Australian Forest Fire Danger Index [160] used as explanatory variable.	No
Wright [241]; to develop empirical models to predict fuel consumption in pine flatwoods forest ecosystems of the Southeastern USA.	Data ($n = 30$) from operational prescribed burns. Shrub consumption ranged from 0.02 to 0.6 kg m^{-2}, and total biomass consumption (of fine fuels and up to 10- hr fuels) varied between 0.1 and 1.6 kg m^{-2}.	Several models proposed for consumption of different fuel components. Fuel consumption a function of pre fire fuel load, season and moisture content variables. Models evaluated against independent data.	Yes
Fernandes and Loureiro [101]; to characterize fuel consumption and the influence of fuel moisture content in surface fires in maritime pine stands, Portugal.	Data ($n = 90$) from prescribed burns at five different locations. Consumption of different surface fuel layers (F and L layers, shrubs). Overall consumption up to 95%.	Proportional fuel consumption for the individual fuel layers, and combination of, modelled through generalised linear modelling using fuel moisture metrics and regional level FWI system [212] codes. Best fit obtained with fuel moisture variables.	No
Volkova and Weston [107]; to establish baseline knowledge of the distribution of forest carbon in eucalypt forests of southern Australia.	Data ($n = 9$) from low-intensity prescribed burns, each one with 4 independent plots for measurements of fuel consumption, and carbon loss and gain.	Consumption given in terms of carbon loss from litter, coarse woody debris, bark and understorey vegetation. Exploratory data analysis.	No
Aponte et al. [108]; to study the effects of repeated low intensity prescribed fires on CWD stocks and attributes in eucalypt forest of south eastern Australia.	Data from low intensity prescribed burns across five sites, each site with five treatments.	Descriptive analysis of the effect of fire on the attributes of coarse woody debris, and long-term stocks.	No
Volkova and Weston [105]; to explore relationships among fuel consumption, or C loss, burn conditions and forest type in planned burns in dry eucalypt forests of SE Australia.	Data from 40 prescribed burns over a range of forest productivity.	Consumption given in terms of C loss from litter and deadwood, but no data presented. Generalised Linear Models developed to explain C loss from predictors such as litter moisture, fireline intensity and forest type.	No
Hollis et al. [242]; to describe woody fuel consumption in southern Australia eucalypt forests and evaluate existing models.	Data ($n = 19$) from prescribed burns and wildfires burning in FORESTCHECK plots [243]. Woody fuel consumption up to 4.5 kg m^{-2}.	Descriptive analysis of data and model fit.	No
Hudak et al. [244]; to relate nadir and oblique fire radiative energy with surface fuel consumption in prescribed burns, USA.	Data from 11 prescribed burn blocks. Fuel consumption range: 1.4–6.4 kg m^{-2}; relative consumption 44–85%.	Fuel consumption derived from both airborne LWIR imagery and various ground validation sensors approached a linear relationship with observed fuel consumption.	Yes
Jenkins et al. [109]; to determine what biomass fractions are typically consumed by a planned fire in southern Australia eucalypt forests.	Data from 9 low-intensity prescribed burns, each one with 4 independent plots for measurements of fuel consumption of overstorey, understorey, coarse woody debris, fine litter and pyrogenic carbon.	Descriptive analysis with quantification of biomass consumption.	No

Table 4 (continued)

Study and objective	Data	Findings	Data published
Sparks et al. [236]; to relate fire radiative flux with tree response; provides fuel consumption data in prescribed burns, USA.	Data from 9 prescribed burns. Fuel consumption up to 6.6 kg m^{-2}.	Analysis does not focus on fuel consumption, but data is provided. Fire propagation data also provided. No analysis of fuel consumption.	Yes
Grau-Andrés et al. [112]; to understand the role of low fuel moisture content in fire severity, as described by fuel consumption, in *Calluna*-dominated shrublands, Scotland.	Data from 19 experimental fires (25 × 30 m) distributed across two contrasting locations. Moss and litter layer consumption measured and given in cm. Consumption up to 5 cm in depth.	Models of moss/litter fuel layer consumption build from fuel moisture content	No
Prichard et al. [33, 245]; to determine whether regionally specific fuel consumption equations were warranted, USA.	Data from 120 prescribed burns in pine dominated forests in the western and south-eastern USA. Consumption of different fuel layers quantified. Total fuel consumption up to 3.4 kg m^{-2}.	Models for consumption of different fuel layers developed for southeastern and western datasets. Fuel consumption explained mostly by pre-fire fuel quantity and for some layers its moisture content. Results warrant development of regional specific models. Data given in [245].	Yes
Hollis et al. [106]; to investigate how the characteristics of woody fuel particles affect the various phases of combustion and their overall effect on fuel consumption; in southern Australia eucalypt forests.	Woody fuel consumption at particle level with 2866 observations. Data is subset of data in [102, 104].	Models for woody volume reduction, ignition success, partial consumption and full consumption developed from General Linear Model analysis. Discussion on the effect of fuel characteristics on woody fuel consumption.	No
Lyon et al. [246]; to understand fire behaviour in masticated fuel treatments in *Pinus ponderosa* stands, USA.	Masticated fuel consumption at plot level. Study based in data from 75 prescribed burns. Provides data from 15 burns. Fuel consumption range: 1.5–8.o kg m^{-2}.	Results explore the relationship between mastication fuel (coarse vs. fine) and dryness conditions with fire behaviour. Results show laboratory derived fire behaviour relationships not to hold to field conditions.	Yes
de Groot et al.[247]; to develop models of canopy fuel consumption for Canadian boreal forest fuel types.	Database comprising experimental fires spreading as surface, intermittent crown, and fully developed crown fires ($n = 59$; 8 distinct experimental burn programs conducted between 1974 and 2000). Canopy fuel consumption varied between 0.0 and 2.2 kg m^{-2}.	Models for canopy fuel consumption given as function of rate of fire spread and canopy fuel load, which was separated into live foliage and fine dead branchwood. Results are discussed within the context of fire behaviour and carbon emissions.	Yes
Price et al. [111]; to improve estimates of total fuel consumption, and its relationship with fire severity and fire type (prescribed burn vs. wildfire) in south eastern Australian eucalypt forests.	Data collected in prescribed fires ($n = 11$), cultural burns ($n = 3$) and wildfires ($n = 6$).	Descriptive analysis of fuel consumption by fuel component and fire severity.	No

Table 5 Objectives, data, and findings of spotting distance or spot fire ignition likelihood studies

Study and objective	Data	Findings	Data published
Gould et al.[30]; to study fire behaviour in dry eucalypt forest (Jarrah, *Eucalyptus marginata*) under dry summer conditions in southern Australia.	Short- and long-range spotting densities and distances in 8 experimental fires. Spotting distances range: 15–1145 m.	Mostly descriptive study. Evaluation of spotting distance models and fitting of spotting density model.	Yes
McCaw et al. [23]; to describe the methodology and results of a series of high-intensity experimental fires in dry eucalypt forest (Jarrah, *E. marginata*) in southern Australia.	Further describes and analyses data from six of the experimental fires in [30].	Mostly descriptive analysis of experimental results.	Yes
Page et al. [117]; to analyse the influence of several environment-, vegetation-, and fire-related variables on maximum spotting distances in wildfires, USA.	Compiled dataset of spot fire distances in wildfires; identified 7214 unique spot fires over the course of 447 different fire-day combinations. Spot fire distance range: <50–2700 m.	Discussion of methodologies used. Descriptive analysis of spot fire distances and spot fire sizes. Mixed effects regression analysis of maximum spot fire distances. A significant positive correlation between the maximum observed spot fire distance and an interaction between fire growth and wind speed were found. Comparison with Albini's [248] maximum spot fire distance model.	No
Storey et al. [119]; to investigate the environmental drivers of long-distance spotting, maximum spot fire distances and number of long-distance spot fires in eucalypt forests, Australia.	Data from 338 wildfire observations. Spot fire distance range: 5.0–13.9 km.	Generalised linear models used in analysis. Wildfire area was the most important predictor of maximum spotting distance. Weather (surface and upper level), vegetation and topographic variables had important secondary effects.	No
Storey et al. [118]; to understand spot fire distance patterns and investigate regional variations associated with fuel type and elevation.	Data used subset of [119] where multiple (>3) spot fires were identified; total of 4219 spot fires used in analysis. Spot fire distance range: 20.0 m-13.9 km.	Study found correlation between spotting distance and density, with noted outliers. Most long-distance spotting associated with a multi-modal distribution, with high numbers of spot fires close to the source and isolated / small clumps of spot fires located far from source. Authors also found considerable regional variation in spotting phenomena.	No

such as LiDAR, to provide detailed 3D maps of the fuel complex structure [126, 127]. This information can then be directly linked with the spatially explicit fire behaviour observations to investigate the direct effect of small-scale fuel features on fire dynamics [127, 128].

Similarly, atmospheric data is often comprehensively measured during such experiments. Networks of ground-based in situ weather stations are used to measure boundary layer wind flow and turbulence around an experimental burn. In some experiments, wind instruments are also located within the experimental plot to measure 3D fluid flow as the fire passes by [124, 129]. The vertical structure of the atmosphere above a fire can be characterised through vertical atmospheric profilers and other instruments, such as Doppler LiDAR and radar systems, and can be used to monitor plume pulse structure and fire-atmosphere interactions [120, 124].

Fire behaviour information collected in integrated measurement campaigns include the basic data measured in studies aimed at the development and evaluation of management-oriented models, including the type of fire (e.g. surface fire, or active crowning), the rate of spread, fireline intensity, and flame length of the head, back of flank fires, and fuel consumption by fuel layer, size class, and condition. A distinct feature of typical integrated measurement campaigns is the collection of more detailed data, namely airborne and tower-based measurements of energy release and radiative and convective heat fluxes [25, 26, 130], flame zone depth [131] and residence time [36] and the near-fire atmospheric conditions including measurements of the number, location and size of fire plumes, entrainment, and turbulence [120, 132]. The detailed measurement of fire behaviour enables plotting of fine scale spatiotemporal maps of fire behaviour metrics that can be co-located with 3D estimates of the fuels complex and fire environment [133]. The inclusion of a broader list of fire behaviour metrics along with a focus on spatial-temporal data collection methods support the evaluation of a wide range of models, offers insights into the mechanisms driving fire behaviour and provide critical data to link fire behaviour to effects and smoke transport [120].

It is worth noting that integrated fire-behaviour measuring campaigns often involve significant investment to bring together the researchers, skills and equipment required to meet the measurement campaign objectives, in addition to the necessary coordination with land and fire managers responsible for safely conducting the large-scale experimental fires under the desired conditions. Ottmar et al. [29], Prichard et al. [120] and McNamara and Mell [133] provide excellent overviews and data requirements for integrated campaigns.

A Global Synthesis of Fire Behaviour Characteristics

The range of fire behaviour characteristics, such as rate of fire spread and fireline intensity vary greatly, both among fuel types and across fire weather conditions. Variation in fire-behaviour characteristics in forests, woodlands, and shrublands is affected by vegetation structure, including the vertical stratification and whether or not fire can transition between fuel layers, namely from surface to canopy fuels. A gradient of increasing surface fire rate of spread in relation to surface fuel layer type is expected in the direction of litter—logging slash—shrub—grass, reflecting the combined effects of fuel particles' fineness and fuel-bed compactness, and this is apparent within a given forest type [e.g. 54]. Also, fires in light grassy fuels and fires in heavy downed woody fuels represent the extremes of the combination between the rate of spread and flame residence time, respectively high-low and low-high, with fires in shrubland and forest in-between [134].

Based on experimental data compiled by [51], Page et al. [134] graphed the general fire behaviour ranges for conifer forests, shrublands, and logging slash, indicating respective approximate maximum values of 5, 3.5, and 2.5 km h^{-1} for the forward rate of fire spread. The weight of Canadian data in their systematization is apparent, and temperate to boreal conifer forests and woodlands in Canada are arguably the forest types for which fire behaviour has been more thoroughly quantified through field experimentation. Faster spreading and higher intensity crown fires occur in black spruce (*Picea mariana*) and jack (*Pinus banksiana*) and lodgepole (*P. contorta*) pine stands, while surface fire is more prevalent in red (*P. resinosa*) and white (*P. strobus*) pine forests and in ponderosa pine (*P. ponderosa*) — Douglas-fir (*Pseudotusga menziesii*) stands [5].

While other surface fuels may be scarce in boreal forests, a distinctive feature is a common presence or dominance of a lichen or moss surface fuel layer with a very fast drying response [135] that can be the main vector for fire spread [136, 137]. The likelihood of crown fire is a combined function of surface fire intensity and canopy base height [87] or of the gap between surface and canopy fuels [85]. Stand structure plays a decisive role in the variability and patterns of fire behaviour in boreal conifer forests, implying that fire type is responsive to short-term variation in wind speed [55, 88] plus spatial variation in canopy fuels [138]. In black spruce-lichen woodland, canopy base height is low enough to facilitate passive crowning [137], as well as in immature jack pine, where in addition extreme stand density favours active crowning [88]. However, the wind speed (fuel moisture) threshold for fire spread is higher (lower) in immature and/or dense conifer stands [55, 75]. Because the likelihood of crown fire related with forest structure decreases as stands mature and vertical continuity decreases [139] and in-stand winds increase [55], the trade-off between stand structure and weather is relevant. The result is a wide fire-behaviour range in mature stands, namely in jack pine – black spruce [140]. Still, crown fire development can be hindered even when the surface fire is intense, e.g., in Siberian Scots pine (*Pinus sylvestris*) stands [141], which is consistent with generally lower wildfire intensity (as inferred from remote sensing) in Eurasian versus in North-American boreal forests [142]. Finally, further fire behaviour exacerbation occurs in crown-fire-prone conifer stands killed by insect outbreaks, namely by the eastern spruce budworm (*Choristoneura fumiferana*) in balsam fir (*Abies balsamea*) [143] and by the mountain pine beetle (*Dendroctonus ponderosae*) in lodgepole pine [144], but a proper understanding of the reasons is lacking [145].

Surface fires are prevalent in the experimental burn programs carried out in non-boreal conifer forests. The transition from surface to crown fire can reflect trade-offs between the nature and quantity of surface fuels. This implies that a fast-spreading fire in light litter-grass often remains a surface fire, as in southeastern USA longleaf pine (*Pinus palustris*) [146–148], whereas a slower-spreading fire in heavy litter-shrub can burn the canopy, as in the maritime pine (*P. pinaster*) case study described by Fernandes et al. [149]. Variation in surface fire behaviour in Mediterranean Basin pine stands (*P. pinaster*, *P. nigra*, *P. brutia*) under mild fuel moisture conditions is driven by wind speed [54, 150, 151], with crowning readily occurring under drier conditions in short or immature stands [100, 152].

In mixed conifer—deciduous broadleaved forests the deciduous component is assumed to moderate fire behaviour proportionally to its relative cover [5, 153], although empirical data showing this effect is non-existent. Consistent quantitative knowledge about fire behaviour in deciduous boreal and temperate forests is limited to the North American quaking aspen (*Populus tremuloides*). Aspen-dominated stands consistently support fire spread only in the fall and early spring (but see [153]), when surface fuel availability (litter plus scattered cured herbs) and exposure to wind are higher and before the overstorey and understorey leaf flush. The windier and/or drier conditions in the experiments of [154] and [155] produced fire-spread rates in the 5–10 m min^{-1} range and flame lengths of ~ 1.5 m. Reports of fire behaviour characteristics in deciduous oak (*Quercus* spp.) and oak-dominated forests in the USA are extensive, but most data pertain to prescribed burning effects studies and reflect an interaction between flame fronts. The seasonal effects mentioned for aspen apply to these, albeit to a lesser extent, and the fire behaviour magnitude is similar. However, faster and more intense fire is likely in oak stands with a litter—shrub understorey surface fuel complex [156, 157].

Other than in eucalypts, fire behaviour experimentation in temperate and Mediterranean evergreen broadleaved forests and woodlands is almost non-existent. Near-surface fuels — i.e. low or prostrated understorey vegetation and suspended litter — are the most significant fuel driver of fire spread in Australian dry eucalypt forests (*Eucalyptus sieberi* [158], ; *E. marginata* [60]), . Depending on weather and fuel conditions, short-range spotting from bark combustion can be a significant driver of forward fire spread [159]. The involvement of eucalypt canopy in fire spread is distinct from observations in conifer forests, with an area of dense spot fire coalescence preceding canopy ignition, i.e. canopy consumption typically occurs behind the flame front leading edge [160]. Experimentation in eucalypt forests has been extensive but most efforts consisted of experiments conducted under dry summer conditions under less than elevated fire danger [159]. The highest rates of spread and flame sizes recorded — up to 23 m min^{-1} and 14 m in [60] — are far from the extremes possible in eucalypt wildfires [159], in contrast with boreal conifer experiments.

Fire in undisturbed tropical evergreen broadleaves is limited to seasonal forests, as fire spread is generally precluded by the high relative humidity prevalent in tall, closed-canopy rainforests [161]. Experimental fire behaviour in these systems has been described for Brazil [77, 162,163,164], Venezuela [161], and Thailand [165], mostly involving point-ignited fires under calm conditions. Forest structure and disturbance history induce variability [166, 167], but rates of spread and flame heights never exceed 1.0 m min^{-1} and 1.0 m, respectively, even in the few instances when low ($< 10\%$) litter moisture content combines with significant wind. Comparatively, deciduous tropical forests (leafless during the hot and dry season) often comprise a grass fuel component and have higher fuel load and less sheltered in-stand conditions (e.g. dry dipterocarp forests in Thailand). This enables faster fire spread rates and taller flames than in evergreen tropical forests, up to 4 m min^{-1} and 1.5 m, respectively [e.g.78, 168, 169].

We previously noted the indirect (through wind speed reduction and dead fuel moisture content increase) but decisive influence of vegetation structure on fire behaviour. In open vegetation types, namely shrublands, such an effect translates into faster fuel-level wind speed and lower fuel moisture in relation to forests, as well as faster drying after rainfall. This degree of exposure, combined with the nature of shrub fuels (fine, elevated, aerated), accounts for the high-intensity fire behaviour observed under low fire danger [7] once the threshold in dead fuel moisture for sustained fire spread is attained, [e.g. 79]; such on/off threshold can be particularly high, as in UK's Calluna spp. heathlands, which is attributed to seasonally low live fuel moisture content [112, 170]. As an example, autumn to spring fire-spread rates in a range of mesic to dry shrublands in north-western Iberia peninsulacan reach up to 15—25 m min-1 [171, 172]. Shrublands are thus intrinsically flammable, notwithstanding substantial variability in physiognomy and fuel characteristics such as load and dead fuel fraction. The effect of wind speed on shrubland fire-spread rate and the correlation with fuel properties are both strong, and the compounded fuel-structure effect is usually attributed to vegetation height or bulk density [e.g.7]. Thus, the current understanding is that shrublands of similar height and cover are expected to show comparable rates of spread if burnt under the same wind speed and dead fuel moisture content, regardless of their floristic composition.

Disruptions in the horizontal or vertical continuity of shrub fuels can hinder or disturb fire spread [80, 173, 174,175]. This is especially relevant in the open shrublands typical of semi-arid environments, which are structurally more heterogeneous, examples including sagebrush (*Artemisia* spp.) [176] and *Prosopis*—*Acacia* [177] in the USA, and mallee-heath in Australia [71]. As a consequence, higher (lower) thresholds in wind speed (dead fuel moisture) are required for sustained horizontal and/or vertical fire spread.

Comparison of fire behaviour characteristics among vegetation types is complicated by the numerous sources of experimental variability in addition to those inherent to fuel characteristics and the range of weather data within each study. Fire development is affected by the method of ignition, i.e. whether ignition points or lines are used, the length of the ignition line, and how the line is established, as well as the size of the experimental plot (see Discussion). Where and how wind speed is measured is a source of substantial variability, relevant factors including the height at which measurements are taken and the density and location of anemometers in relation to the plot, the period and rate of sampling, and whether they are placed in-stand or in open terrain [55, 178, 179]. Finally, how rate of spread is measured and calculated also matters [141, 180]. Ultimately, and considering all the experimental set-up variation, all fire behaviour field studies are unique.

Within the BONFIRE database [181], we considered the studies comprising a minimum of 5 experimental fires, $n = 92$ (Supplementary material). We calculated the study means of forward fire-spread rate and its two main environmental drivers (wind speed and fine dead fuel moisture content), plus ignition line length given the scale-dependency of fire behaviour. Plots of fire-spread rate versus these variables (Fig. 1 for forests, and Fig. 2 for woody but treeless

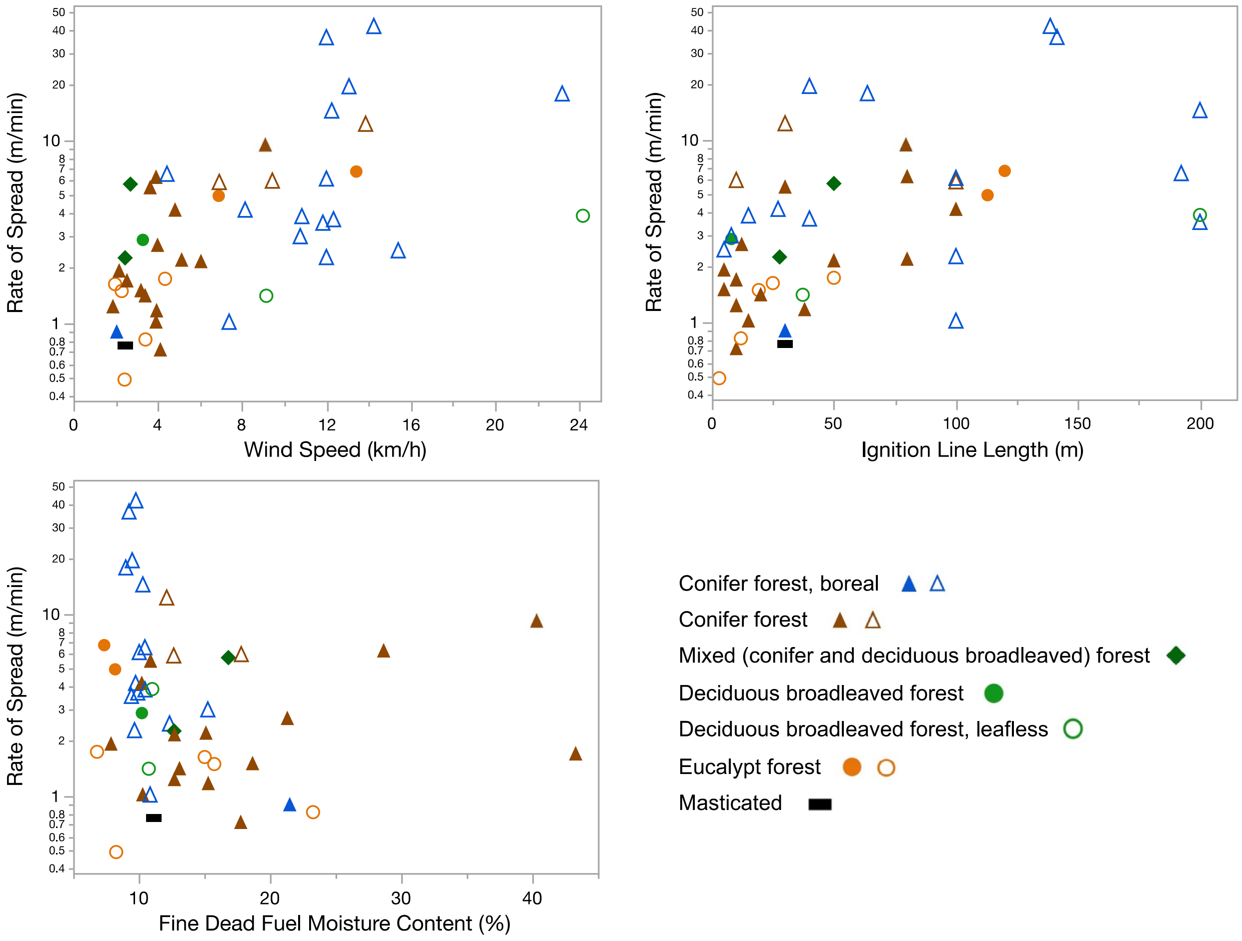

Fig. 1 Variation of experimental forward fire-spread rate in forest as a function of wind speed, fine dead fuel moisture content, and ignition line length. Solid and open symbols respectively denote experiments where wind was measured inside the stand at a height of 1.5–2 m, or at 10-m in the open. Data sources are presented as supplementary information

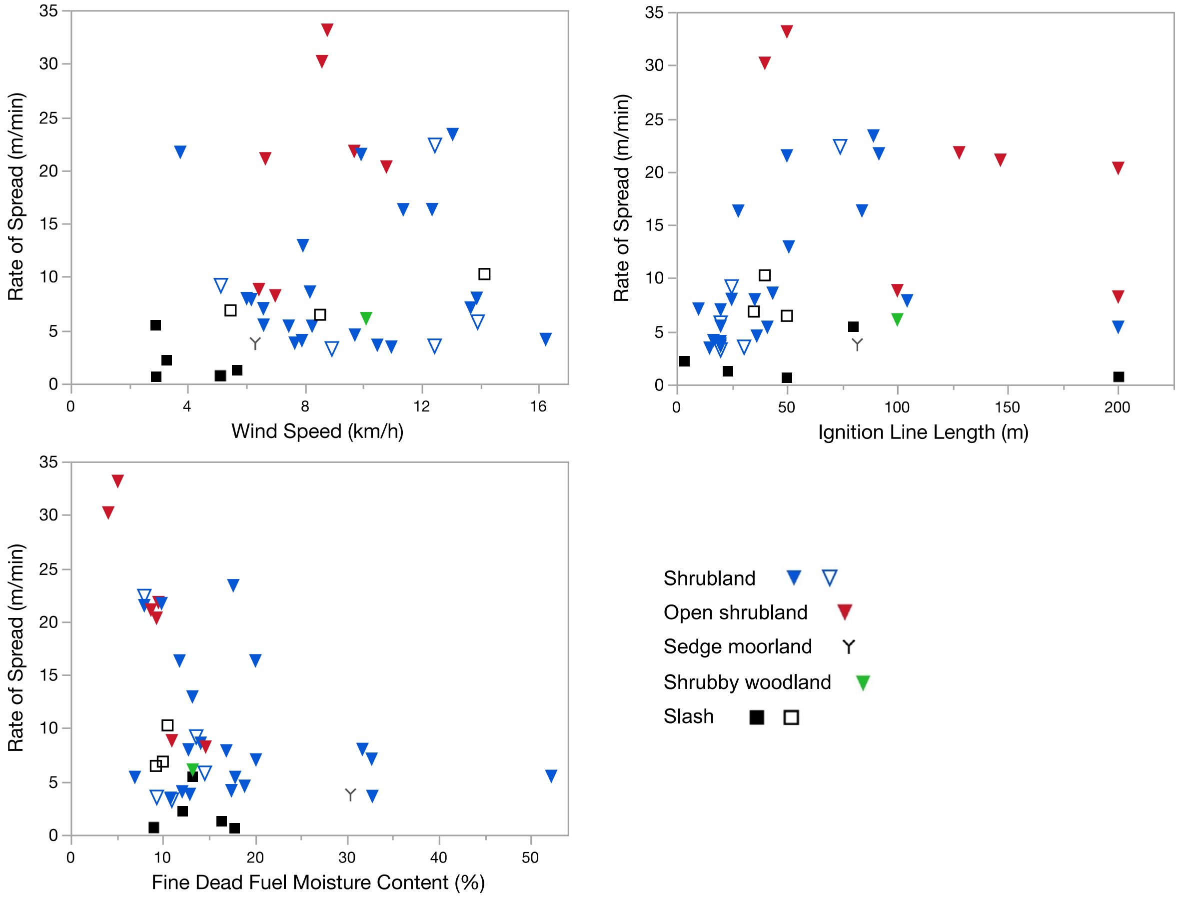

Fig. 2 Variation of experimental forward fire-spread rate in woody open vegetation types, including forest slash, as a function of wind speed, fine dead fuel moisture content, and ignition line length. Solid and open symbols respectively denote experiments where wind was measured at a height of 1.5–2 m, or at 10-m in the open. Data sources are presented as supplementary information

environments) show rate of spread varying by approximately one order of magnitude for any given value of each independent variable and suggest increased variability for conditions increasingly favourable for fire spread.

The observed scatter is substantial, but the collective patterns conform to results from individual studies [182]: the fire-spread rate response to wind speed, dead fuel moisture content, and ignition line length, respectively, follows a near-linear increase, a non-linear decay, and a steep increase to a plateau up to an ignition length of 50–100 m. To quantify the drivers of rate of fire spread, we modelled its log-transformed form from fuel type, generic type of vegetation (forest or non-forest), and log-transformed wind speed and ignition line length. These variables (all significant at $p < 0.01$) accounted for 64.1% of the existing variation, with relative effect sizes of 4.8 (fuel type), 3.4 (wind speed), 2.8 (ignition line length), and 1 (vegetation type). Fuel moisture content was inversely autocorrelated with ignition line length ($p = 0.042$) and was associated to fuel type ($p = 0.0040$) and its inclusion in the model was not warranted ($p > 0.05$). The fuel-type effect is also likely confounded with the experimental idiosyncrasies of the various studies — including slope (although 75% of the studies were carried out on slopes of < 5°) and fuel characteristics — and so its actual influence should be lower. Wind-measurement height was not influential, but all the stronger wind speeds in forest experiments were measured at 10-m in the open; Fig. 1 suggests that adjustment (reduction) to in-stand surface conditions (~ 2-m height) would increase the ability of wind speed to explain fire-spread rate variability.

The fastest fires in forest were observed in boreal conifers, where less conservative burn conditions are more represented, i.e. stronger wind, lower dead fuel moisture content, and larger plot size, clearly contrasting with non-boreal conifers. Thus, it is not possible to ascertain if boreal conifer forests are intrinsically more prone to high-intensity crown fire in comparison with conifer forests elsewhere. The number of studies available for other forest types is limited and precludes sound comparisons, but the scatter in Fig. 1 is consistent with the description made early in this section.

The response of fire-spread rate to wind speed and ignition line length appears more scattered in open woody vegetation than in forest (Fig. 2). Open shrubland recorded the highest spread rates, coinciding with distinctly lower fuel moisture contents. Fire-spread rate in slash fuels does not reach the expected potential [5], given the prevalence of weak winds, moderately high fuel moistures, and relatively short ignition lengths. Again, generalization of differences between vegetation types is not allowed by the data.

Discussion

A Note on Ignition Type and Experimental Fire Size

Many of the main flame front and wildfire behaviour properties, such as spread rate and radiative heat transfer are scale dependent [7, 183]. Ignition type (e.g. point versus line) and pattern will influence how fire propagates and the behaviour it exhibits. Plot size may hinder the flame front reaching the pseudo-steady-state rate of fire spread by limiting the length of the ignition line [6, 7]. Also, plot size may reduce the representativeness of fire measurements because some distance is required for a fire to attain the pseudo-steady-state condition [184]. As such, a small-scale experimental fire might not exhibit the dynamics expected to be observed in a wildfire propagating at a pseudo steady state for the prevailing burning conditions. Similarly, an experiment ignited through a complex ignition pattern to replicate prescribed fire behaviour will not represent the behaviour of free spreading wildfire.

In Australian dry eucalypt forests, an instantaneous 120-m long ignition line was found to quickly (within 25 m) produce a free spreading fire in equilibrium with the conditions under moderate to high fire spread potential [23, 30]. The size of the required ignition line length to quickly attain a pseudo-steady state is dependent on burning conditions [184] and has not been adequately quantified in other forest and shrubland fuel types. Similarly, the size of a fire run, or multiple runs when considering micro-plots [185], should cover a long enough period that integrates the transient nature of wind flow, i.e., including at least a full wind gust/lull cycle [71, 186]. When considering the results described in the previous section, it was found that a large number of experimental campaigns produced fires that were likely not in equilibrium with the environment and more likely were still undergoing the development phase [187]. An analysis of published research results needs to consider the motivations and objectives driving the studies (e.g., an intensive small-scale study vs. large scale project driven by operational needs), and the commensurate constraints related to funding and ignition of outdoor fires in fire-prone landscapes. Often the size of the experimental fires and their intensity are a compromise between the aims of the researchers and the restrictions imposed by academic, operational, financial, safety and legal considerations. Care nevertheless should be taken when amalgamating data from different datasets, as experimental fire size and environmental and fire measuring methods can differ substantially and lead to biases.

The Role of Wildfire Data

For years, wildfire data has had an important role in the development of operationally relevant, empirically based, fire spread rate models applicable for wildfire spread prediction [5, 97] and the evaluation of fire spread models developed from experimental fire data [7, 60, 62, 188]. Wildfire data has also been used to investigate the importance of the detailed description of fire – atmosphere coupling in understanding and better modelling wildfire propagation [e.g. 189, 190, 191].

Wildfires tend to occur at unexpected and remote locations, often not easily accessible to researchers, and their violent nature makes them life threatening events, and not easily amenable for direct study. In the past, wildfire data has been often derived from careful documentation of observations of wildfire events into case studies [192]. In more recent years, the availability of detailed fire management agency records in digital formats and modelled spatially-explicit fuel and weather data, coupled with the widespread use of new remote sensing tools, such as thermal infrared imagery, have allowed the development of large wildfire behaviour datasets [56, 117, 119, 144, 193–195]. Use of satellite infra-red sensors have also potential to capture fire propagation in wildfire settings [196], although temporal and spatial resolution limit the accuracy and frequency of measurements. An important consideration in using wildfire data is the rather high uncertainty in these datasets compared to what can be obtained in a dedicated experiment. Nonetheless, what is lost in accuracy and detail is gained in insights into fire processes that cannot be gathered in even the largest of experimental fires. These datasets can further support not only the development [194] and evaluation of empirical fire behaviour models as described above, but also the study and modelling of other less commonly studied, but very important phenomena, such as fire-atmosphere interactions [197–199], fire whirls [200, 201] and large scale vortices development [201, 202] and vorticity-driven lateral spread [203, 204], just to name a few.

Conclusions

Empirical field-based observations and measurements of fire behaviour are the foundation of our understanding of the complex processes determining wildland fire propagation and the basis of existing operational models describing the effects of environmental variables on prescribed burn and wildfire behaviour. As we connect distinct fire behaviour datasets collected over the past two decades from across the world, it is clear that there is a considerable amount of ‘noise’ that precludes a comprehensive and robust analysis of fire behaviour trends.

Two main issues contribute to this. Firstly, there is no defined or accepted best practice for the measurement of the behaviour of free-spreading landscape fires. Methods used to sample fire behaviour, weather and fuel variables vary widely between studies and can include direct, derived and interpolated estimates of key drivers of fire behaviour. Fire behaviour fuels and weather data uncertainty are likely to vary widely across different studies depending upon the instrumentation. Direct measures at the point or small scale are likely to have the lowest uncertainty while estimates that are interpolated from point measures or derived from a proxy measure are likely to have larger uncertainties. Methods used in any study are often a compromise as a consequence of constraints imposed by the availability of resources and operational and safety considerations. It is also important to recognize that our understanding of fire behaviour phenomena and our ability to use fire behaviour data to evaluate various models depend in part on these uncertainties.

Secondly, the transient nature of fire propagation and behaviour, due primarily to the small-scale variability in environmental conditions, adds inherent noise to fire behaviour observations, particularly in smaller experimental fires. Large experimental fires are required to capture mean fire behaviour conditions for the environment under which a fire is spreading [179, 186]. These issues point out the need for the research community to define a set of best practices and minimum requirements to guide future experimental fire behaviour research.

The validity of fire behaviour data collected in field conditions is paramount when one of the uses of the data is the parameterization and evaluation of fire behaviour models aimed at supporting fire management decision making. Biases in the data collected will result in erroneous model behaviour that can compromise forest and fire management practices with long-term negative impacts.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare they have no conflict of interest.

Competing Interests The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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