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Fireline production rate of handcrews in wildfires of the Spanish Mediterranean region

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ABSTRACT

Background. Handcrews dig handlines to bare mineral soil for fire containment. Increasing the amount of firefighting resources is insufficient to mitigate wildfire damage or decrease the number of large fires. **Aims.** This study aims to empirically assess handcrew fireline production rates through direct monitoring of suppression actions on active wildfires. **Methods.** A database was created from information gathered by crew supervisors during wildfires in southern Spain between 2014 and 2019. Fireline production rates were calculated from working time and handline length. **Key results.** Mean fireline production rate during direct attack in chaparral was 0.33 m min^{-1} $firefighter^{-1}$, whereas production in timber litter was 1.06 m min^{-1} $firefighter^{-1}$. However, fireline production rate was considerably reduced during indirect attack, in fuel types with high fuel loading, on wildfires larger than 50 ha, after 3 h of sustained suppression action, with crews of more than nine firefighters, in unsuccessful fire containment, and when the ground crews lacked aerial support. **Conclusions.** Our results suggest mean fireline production rates need to be modified by working conditions and psychological variables to better inform efficient acquisition and allocation of resources. **Implications.** Knowing the operating capability of firefighting resources is important to fire managers for reducing uncertainty and guaranteeing the safety and effectiveness of suppression.

Keywords: aerial resource support, crew size, direct and indirect attack, fire containment success, firefighter productivity and safety, fuel model, suppression effectiveness, working time.

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Introduction

Changing environmental and social conditions affect fire regimes by promoting fuel build-up and fuel availability for combustion (Pausas and Fernández-Muñoz 2012; Galizia *et al.* 2022). These two primary alterations increase the number of large wildfires and extreme fire behaviour events, often leading to significant ecological and socio-economic impacts (Flannigan *et al.* 2009; Bowman *et al.* 2017; Ruffault *et al.* 2018; Galizia *et al.* 2022), as well as increases in firefighting costs (Calkin *et al.* 2015; Rodríguez y Silva *et al.* 2020). In the United States, wildfire management currently comprises over 50% of Forest Service expenditures (Calkin *et al.* 2014). In the Mediterranean Region, an increase of 65–86% in suppression costs has been observed over the last decade (Molina *et al.* 2019).

Larger and more intense wildfires increase demand for firefighting resources. However, resources are finite and often become scarce, and increasing their amount does not guarantee mitigation of wildfire damage or a decrease in the number of large fires (Rytwinski and Crowe 2010; Fernandes *et al.* 2016; O'Connor *et al.* 2022). Consequently, optimising wildfire resource acquisition and allocation becomes essential for fire management. Accurate fireline production rate knowledge is needed (Broyles 2011; Dunn *et al.* 2017) to optimise the effectiveness of wildfire suppression resources (Katuwal *et al.* 2016; Rodríguez y Silva and González-Cabán 2016; Thompson *et al.* 2018). This is particularly important for handcrews because they remain one of the most effective tools for containing and controlling wildfires, digging handlines directly along a fire edge or indirectly at some distance from the fire (Broyles 2011). However, accurate fireline production rate data are scarce in different fuel types and under varying fire conditions, limiting the ability to effectively optimise their acquisition and use. The need to optimise effectiveness becomes even more meaningful and essential in simultaneous fire events, when the availability of resources is limited and appropriate assessments and prioritisations are required.

A primary challenge in estimating suppression resource productivity lies in obtaining a reliable dataset for a multivariate analysis (Plucinski 2019*a*), especially given observed variability and uncertainty in productivity estimates (Haven *et al.* 1982; Hirsch and Martell 1996; McCarthy *et al.* 2003). Significant differences between typologies of suppression resources interacting with heterogeneity of the fire environmental (fire weather, vegetation and topography) increase this uncertainty (Thompson and Calkin 2011; Rodríguez y Silva and González-Cabán 2016), and productivity models developed using non-wildfire data grossly overpredict fireline production rates (Haven *et al.* 1982; Plucinski 2019*b*). However, researchers have used several methods to estimate suppression resource productivity (Plucinski 2019*b*). For example, Holmes and Calkin (2013) estimated the productivity of firefighting resources (handcrews, dozers, engines and helicopters) on large wildfires using a Cobb–Douglas production function, and Katuwal *et al.* (2016) used a stochastic frontier analysis. Similarly, Rodríguez y Silva and Hand (2018) carried out a comparative study of the productivity of suppression operations using the Cobb–Douglas and Constant Elasticity of Substitution functions. More directly, expert knowledge has been used to estimate productivity during initial attack (Fried and Gilless 1989), Jiménez (2014) assessed handcrew fireline production rate on firefighting training in Spain, and some studies (Broyles 2011; NWCG 2021) have estimated fireline productivity through direct observations of handcrews on active fires in the United States, albeit under a limited range of environmental conditions.

The aim of the present study was to assess fireline production rates of handcrews during firefighting through direct observations tracked with global positioning systems (GPSs) on active fires in Spanish Mediterranean ecosystems. In this sense, handcrew fireline production rate is defined as the expected length of fireline that can be created by a firefighter in a given period of time (Broyles 2011).

Empirical assessment of suppression effectiveness has had many practical applications including as inputs for decision making (Plucinski 2019*b*). Moreover, as Broyles (2011) proposed, production rates could be used for planning purposes such as optimisation of crews (avoiding understaffed or overstaffed firefighting units), resource pre-positioning during high fire danger times, fire growth estimation modelling, and comparing the estimated costs with the values protected. The expected added value of this research is, mainly, to reduce uncertainty in Mediterranean wildfire suppression resource needs as social and environmental conditions change. Our results provide valuable information for deciding suitable assignment of resources to achieve objectives while maintaining firefighter safety.

Materials and methods

Study area

This research was conducted in three Spanish regions – Andalucía, Castilla-La ManchaMancha and Comunidad Valenciana – located in the southern Iberian Peninsula (Fig. 1). The study area covers 190254 km^2 of alternating flat and mountain areas, including the highest point of the Iberian Peninsula (3479 m above sea level (asl)). The study area is characterised by a Mediterranean climate of dry summers, with the average maximum daily temperature often above 40°C and the average minimum daily relative humidity under 30%. These weather conditions are conducive to fire ignition and spread. An average of 645 wildfires per year occur in each of these regions (2008–2020), burning an average of 7492 ha annually per region (Castilla-La Mancha 2023; Generalitat Valenciana 2023; Gobierno de España 2023; Junta de Andalucía 2023).

The most representative forests are dominated by *Quercus ilex* L., *Quercus suber* L., *Pinus halepensis* Mill., *Pinus pinaster* Ait. and *Pinus pinea* L. Shrub is dominated by *Cistus* spp., *Erica* spp., *Quercus coccifera* L., *Pistacia lentiscus* L., *Salvia rosmarinus* L., *Thymus mastichina* L. and *Lavandula stoechas* L. In Andaluscía and Castilla-La Mancha, there are also oak savannas that are artificial agroforestry ecosystems comprising *Quercus* trees in low density with a grass understory, commonly used for livestock grazing or croplands. This vegetation is highly flammable in summer with low moisture contents.

Field data gathering

The handcrew fireline production rate database was created with the support of fire agencies from the three regional governments involved. The handcrew work assessed in this research consisted of digging handlines to mineral soil directly along a fire edge (direct attack) or indirectly at some distance from it (indirect attack). Firefighters used a combination of hand tools (Pulaskis, hoes and McLeods) and chainsaws in both attack types. Only handlines with or without helicopter aerial drop support were considered. Other combinations of suppression resources were not studied. Extinguishing fires requires additional work of mopping up (i.e. removing heat with water or dirt) and was not considered in this research. Field data were gathered by crew supervisors. After each firefighting mission, crew supervisors completed an assessment form that included the variables that made up our dataset (Table 1). We provided technical and supervised training in data collection to reduce bias and subjectivity.

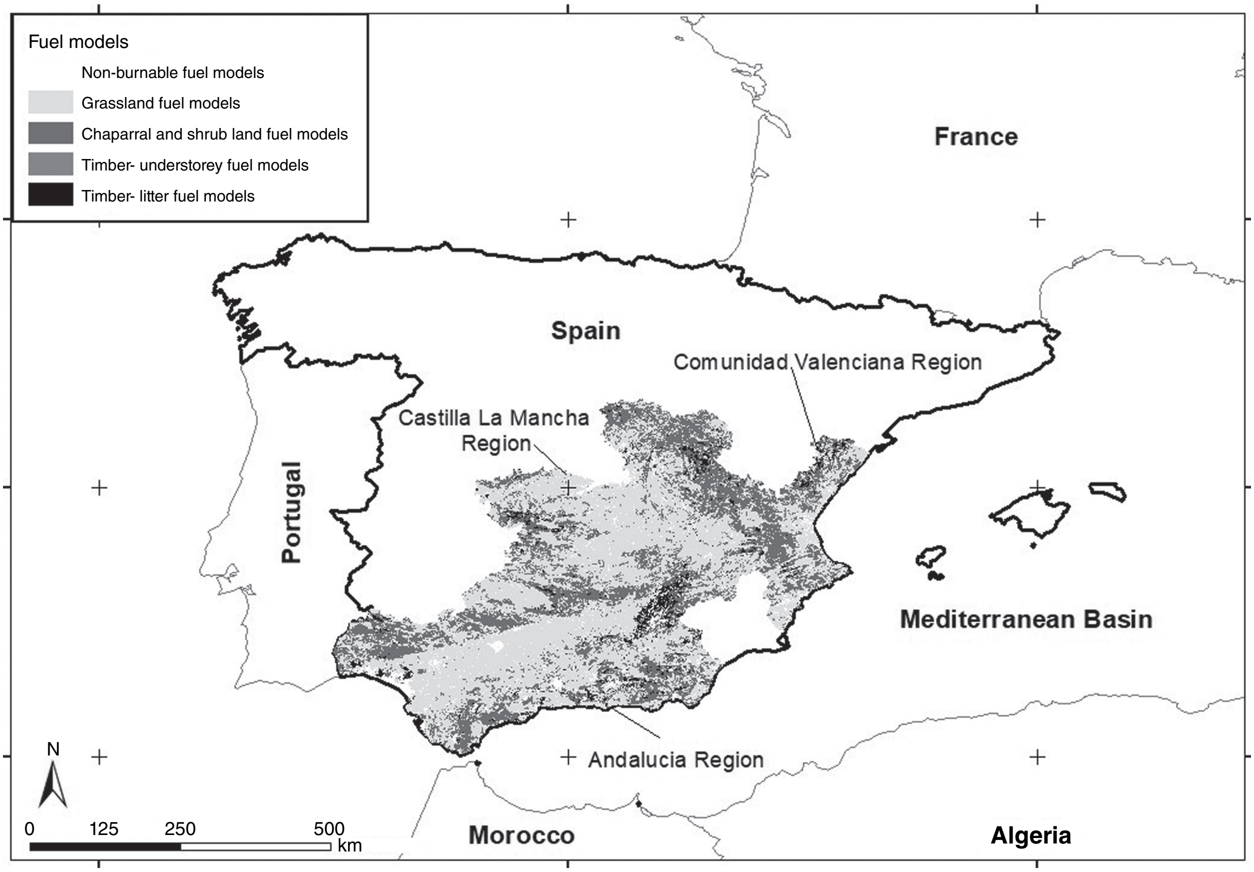

Fig. 1. Study area location.

Our research is at the fire incident scale. Weather variables (temperature, relative humidity and wind speed) and others such as slope, stoniness, fuel model, fire size, crew size, attack type, aerial resource support, time between aerial resource drops, fire containment success, working time and handline length are considered for the handcrew fireline production rate assessment. Each of the studied variables is explained below and their ranges are detailed in Table 1.

- Fire event general information: identification, date, time, administrative area and final fire size (<1, 1–50, >50 ha).
- Weather variables during working time: temperature (°C), relative humidity (%) and wind speed (km h^{-1}). This information was collected by crew supervisors with portable weather stations (Kestrel), handheld devices that provide local data recording. Therefore, weather data referred to the place and time of firefighter work, considering wildfire environment dynamics. The weather data used for statistical analyses are the average of the set of weather observations collected with random frequency during the working time.
- Land variables: slope (0–15, 15–30, 30–45 and >45%) and stoniness (≤25, 25–50, 50–75 and >75%). Stoniness is defined as the percentage of land surface horizontally occupied by stones. Land variable values were assigned based on visual estimations of crew supervisors.
- Fuel model (Table 2). The most representative fuel model in the firefighting area in each wildfire was identified. Pictures were taken to check proper fuel model selection. Although there are more up-to-date fuel model classifications (Scott and Burgan 2005; Rodríguez y Silva and Molina-Martínez 2012), the categorisation developed by Anderson (1982) was used to minimise the bias associated with fuel model misidentification and to be able to make appropriate comparison between different studies. Commonly known as the Rothermel fuel models, the ones identified in the study area were grouped into five types: grass (Rothermel fuel models 1, 2, 3), chaparral (Rothermel fuel model 4), shrub (Rothermel fuel models 5, 6), timber understory (Rothermel fuel models 7, 10) timber litter (Rothermel fuel models 8, 9).
- Suppression resources: crew size (<7 firefighters, 7–9 firefighters and >9 firefighters), attack type (direct or indirect attack), aerial resource support (with and without aerial resources) and time between aerial resource drops (min). The crew size varied between fires

Table 1. Study variable ranges.

Variable	Range
Year	2014–2019
Wildfire season (month)	June–September
Fire size (ha)	0.50–3400
Temperature (°C)	21–41.50
Relative humidity (%)	8–52
Wind speed (km h^{-1})	2.50–60
Slope (%)	Low (0–15), medium (15–30), high (30–45) and very high (>45)
Stoniness (%)	Low (≤25), medium (25–50), high (50–75) and very high (>75)
Crew size (firefighter numbers)	5–27
Attack type	Direct and indirect
Aerial resource support	No and yes
Time between aerial resource drops (min)	3–30
Fire containment success	Unsuccessful and successful
Working time (min)	20–605
Fireline production rate (m min^{-1} $firefighter^{-1}$)	0.10–2.85

Table 2. Fuel model characterisation (Anderson 1982).

Fuel model (Anderson 1982)	Fuel type	Description
1	Grass	Short grass (0.30 m)
2		Grass and shrub covering one-third to two-thirds of the surface
3		Tall grass (0.75 m)
4	Chaparral	Chaparral
5	Shrub	Shrub (0.60 m)
6		Dormant brush
7	Timber understory	Understory–pine overstory
8	Timber litter	Closed timber litter
9	Timber litter	Hardwood litter
10	Timber understory	Timber (litter and understory)

agencies. Moreover, this research considered the combination of several handcrew units working together like a single unit. The difference between direct and indirect attack lies in the handline being at the fire edge (direct attack) or at a distance from the fire (indirect attack). This research only considered the influence of helicopters as aerial resources that supported handcrews by dropping water.

- Fire containment success (successful and unsuccessful). This variable refers to wildfire control capability of the handline developed by firefighters. Spotting is considered as successful or unsuccessful fire containment depending on whether or not a fire that starts on the other side of the handline is put out by the analysed crew.
- Working time (min) and distance (handline length) (m). Distance measurements were gathered using GPS. It is considered effective working time, including rest breaks but excluding travel time (driving or hiking). Working time is divided into three meaningful categories (<60, 60–180 and >180 min).
- Fireline production rate per firefighter (m min^{-1} $firefighter^{-1}$) was calculated as the ratio between handline length and total working time in a single wildfire.

The productivity dataset was generated from fire events during six wildfires seasons (2014–2019). A total of 229 assessment forms were collected, of which 204 reports were used for this study; 25 reports were removed from the analysis owing to either contradictions or lack of information.

Field data analyses

The georeferenced data of the firefighting crew suppression work (recorded via GPS) were statistically analysed. We estimated handcrew fireline production rate as the mean value per fuel type (grass, chaparral, shrub, timber understory and timber litter) and attack type (direct and indirect attack). We tested for normal distributions using Kolmogorov-Smirnov tests owing to the sampling size (more than 50 samples), and found our estimates of fireline production rate had a non-normal distribution. Therefore, we used a Kruskal–Wallis test to identify significant differences ($P < 0.05$) among fuel type and attack type. We also used the Kolmogorov–Smirnov, Mann–Whitney *U* and Kruskal–Wallis tests to test for significant differences according to fire size, working time, crew size, fire containment success and aerial resource support. Mann–Whitney *U* was developed for variables grouped into two categories (fire containment success and aerial resource support) and Kruskal–Wallis for variables grouped into three or more categories (fire size, working time, crew size). We used SPSS© software for all statistical analyses.

Lastly, we modelled positive or negative effects in handcrew fireline production rates, using linear and non-linear regression models. We randomly selected 80% of the dataset for model training, and reserved 20% for evaluation. We selected our best models based on the highest coefficient of determination (R^2) and lowest mean absolute error (MAE). Consistent with this, the real production rate would be the

Table 3. Fireline production rate per fuel type according to attack type.

Fuel type	*n*	Fireline production rate ($m\ min^{-1}$ firefighter^{-1}) Direct attack	*n*	Fireline production rate ($m\ min^{-1}$ firefighter^{-1}) Indirect attack	*n*
Grass	68	0.87 (±0.45)[a]	58	0.40 (±0.16)[a]	10
Chaparral	24	0.33 (±0.19)[b]	18	0.31 (±0.12)[a]	16
Shrub	75	0.67 (±0.34)[c]	65		
Timber understory	29	0.44 (±0.17)[b]	21	0.16 (±0.04)[b]	10
Timber litter	8	1.06 (±0.1)[d]	6		

Standard deviation is given in parentheses. Mean values in a column followed by the same letter are not significantly different ($P < 0.05$).

result of multiplying the standard rate by a coefficient of increase or reduction (Eqn 1):

$$R' = c \times R \qquad (1)$$

where R' is the real production rate ($m\ min^{-1}$ firefighter^{-1}), c is the reduction coefficient (working time) or increase coefficient (aerial resource support) and R is the standard production rate ($m\ min^{-1}$ firefighter^{-1}).

Results

According to our findings, the average firefighter fireline production rate ranged from 0.10 to 2.85 $m\ min^{-1}$ firefighter^{-1}, varying based on the different study variables (fuel type, attack type, environmental characteristics, fire size, working time, crew size, fire containment success and aerial resource support). The following sub-sections detail the influence of these variables on the handcrew fireline production rates in Spanish Mediterranean areas. In addition, modelling of the effect of working time and aerial resource support on fireline production rates is included in the corresponding sub-sections.

Fireline production rate per fuel type

According to our statistical analyses, significant differences ($P < 0.05$) were observed based on attack type and fuel types (Table 3). For all fuel types, fireline production rates were higher in direct attack than in indirect attack. During direct attack, production rates varied in four statistically significant ($P < 0.05$) groups based on fuel type: grass, chaparral and timber understory, shrub, and timber litter. The highest production rate was associated with timber litter fuel types (1.06 $m\ min^{-1}$ firefighter^{-1}) and the lowest rate was measured in chaparral fuel type (0.33 $m\ min^{-1}$ firefighter^{-1}). Grass showed higher rates (0.87 $m\ min^{-1}$ firefighter^{-1}) than timber understory fuel types (0.44 $m\ min^{-1}$ firefighter^{-1}) and shrub (0.67 $m\ min^{-1}$ firefighter^{-1}). During indirect attack, fireline production rates varied by two statistically significant ($P < 0.05$) groups based on fuel type: grass, chaparral and shrub, timber understory and timber litter. Fireline production rate was significantly higher in grass (0.40 $m\ min^{-1}$ firefighter^{-1}) and chaparral and shrub (0.31 $m\ min^{-1}$ firefighter^{-1}) than in timber fuel types (0.16 $m\ min^{-1}$ firefighter^{-1}).

Table 4. Fireline production rate per fire size.

Fire size (ha)	*n*	Fireline production rate ($m\ min^{-1}$ firefighter^{-1})
<1	96	0.67 (±0.55)[a]
1–50	61	0.55 (±0.43)[a]
>50	47	0.41 (±0.25)[b]

standard deviation is given in parentheses. Mean values in a column followed by the same letter are not significantly different ($P < 0.05$).

Fireline production rate per environmental characteristic

Weather conditions (temperature, relative humidity and wind speed) and land characteristics (slope and stoniness) were not statistically significant factors for each fuel type based on our Kruskal–Wallis tests. However, wind speeds above 50–60 $km\ h^{-1}$ reduced production rates and we observed a 33.83% higher fireline production rate in contour lines than in the steepest slope.

Fireline production rate per fire size

Significant differences ($U = 244$, $P < 0.05$) were identified between fire sizes. We observed a negative correlation between fireline production rate and final fire size (Table 4). The fireline production rate decreased from fires smaller than 1 ha (0.67 $m\ min^{-1}$ firefighter^{-1}) to fires larger than 50 ha (0.41 $m\ min^{-1}$ firefighter^{-1}).

Fireline production rate per working time

Although fireline production rates were not significantly modified with the working time in grass fuel models, significant differences ($U = 163$, $P < 0.05$) were observed in shrub between the first hour of work (0.67 $m\ min^{-1}$ firefighter^{-1})

and more than 3 h of work (0.39 m min^{-1} firefighter^{-1}) (Table 5).

The reduction of the mean fireline production rates due to working time was modelled with a logarithmic model (Table 6 and Fig. 2). The coefficient of determination is 0.82 and the MAE is 0.10 m min^{-1} firefighter^{-1}. The range of the variable modelled (working time) is from 20 to 605 min.

Table 5. Fireline production rate per working time in shrub.

Working time (min)	*n*	Fireline production rate (m min^{-1} firefighter^{-1})
<60	36	0.67 (±0.54)[a]
60–180	20	0.52 (±0.28)[a]
>180	19	0.39 (±0.27)[b]

standard deviation is given in parentheses. Mean values in a column followed by the same letter are not significantly different ($P < 0.05$).

Table 6. Working time reduction factor and aerial resource support increase factor.

Model form	Parameter	Estimation	*P*	R^2	MAE
$c_1 = a\ln(x) + b$	*a*	−0.21	<0.01	0.82	0.10
	b	1.45			
$c_2 = a\ln(y) + b$	*a*	−0.20	<0.01	0.87	0.09
	b	1.45			

x is the working time (min), c_1 is the working time reduction factor, c_2 is the aerial resource support increase factor, *y* is the time between aerial resource drops (min).

Fireline production rate per crew size

We observed the lowest fireline production rates in crews made up of more than nine firefighters, relative to other crew sizes (Table 7). However, we did not observe statistically significant differences in fireline production rates according to crew size (number of firefighters) in grass, ranging from 0.9 m min^{-1} firefighter^{-1} (more than nine firefighters) to 1.02 m min^{-1} firefighter^{-1} (less than seven firefighters). Nevertheless, we observed significant differences ($U = 93.50$, $P < 0.05$) in shrub production rates between fire crews with more than nine firefighters (0.33 m min^{-1} firefighter^{-1}) and fire crews with less than nine firefighters (0.55–0.68 m min^{-1} firefighter^{-1}), and did not observe significant differences between less than seven firefighters and fire crews between seven and nine firefighters.

Fireline production rate per fire containment success

Wildfire containment success positively affected the fireline production rate in both grass and shrub fuel types (Table 8). The lowest fireline production rates ensued when the suppression work of a crew was unsuccessful. Although no significant differences were observed in grass, meaningful differences were found in shrub ($U = 81.90$, $P < 0.05$),

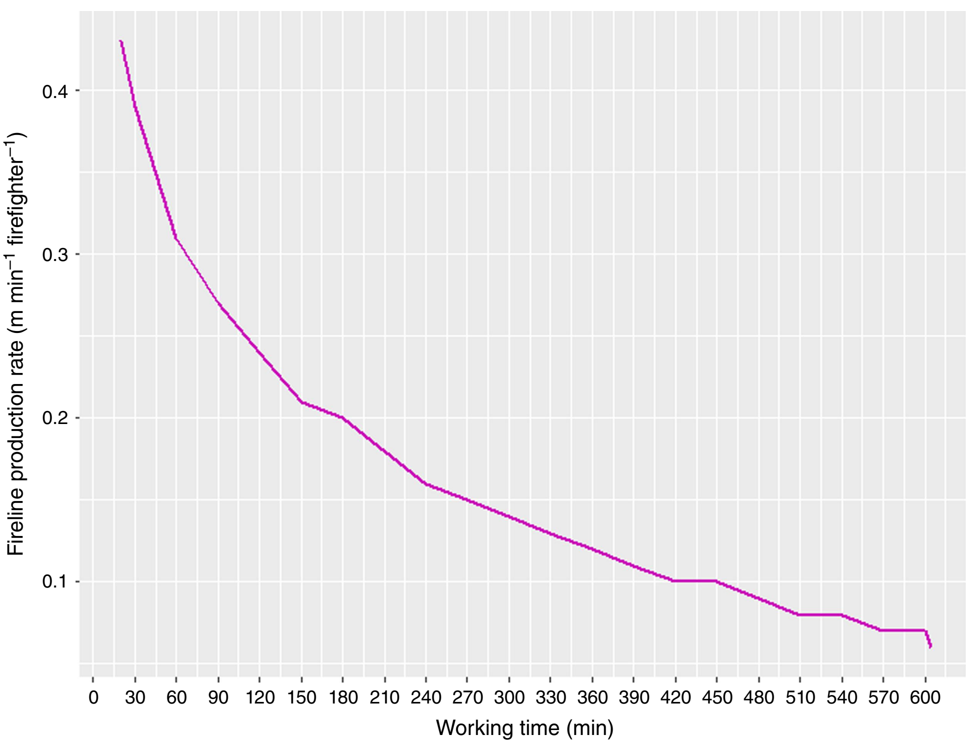

Fig. 2. Handcrew fireline production rate reduction due to working time.

Table 7. Fireline production rate per crew size according to fuel types.

Crew size (firefighter number)	n	Fireline production rate in grass ($m\ min^{-1}$ $firefighter^{-1}$)	n	Fireline production rate in shrub ($m\ min^{-1}$ $firefighter^{-1}$)	n
<7	50	1.02 (±0.65)[a]	23	0.68 (±0.47)[a]	27
7–9	73	0.77 (±0.57)[a]	35	0.55 (±0.35)[a]	38
>9	20	0.90 (±0.42)[a]	10	0.33 (±0.26)[b]	10

standard deviation is given in parentheses. Mean values in a column followed by the same letter are not significantly different ($P < 0.05$).

Table 8. Fireline production rate per fire containment success according to fuel types.

Fuel type	n	Unsuccessful fire perimeter containment ($m\ min^{-1}$ $firefighter^{-1}$)	n	Successful fire perimeter containment ($m\ min^{-1}$ $firefighter^{-1}$)	n
Grass	68	1.09 (±0.15)[a]	20	1.16 (±0.42)[a]	48
Shrub	75	0.33 (±0.09)[a]	19	0.61 (±0.29)[b]	56

s.d. is given in parentheses. Mean values in a row followed by the same letter are not significantly different ($P < 0.05$).

Table 9. Fireline production rate per aerial resource support according to fuel types.

Fuel type	n	Fireline production rate with aerial resource support ($m\ min^{-1}$ $firefighter^{-1}$)	n	Fireline production rate without aerial resource support ($m\ min^{-1}$ $firefighter^{-1}$)	n
Grass	68	0.87 (±0.30)[a]	52	0.79 (±0.45)[a]	16
Shrub	75	0.63 (±0.39)[a]	51	0.51 (±0.20)[b]	24

standard deviation is given in parentheses. Mean values in a row followed by the same letter are not significantly different ($P < 0.05$).

in which fireline production rates with unsuccessful fire perimeter containment ($0.33\ m\ min^{-1}$ $firefighter^{-1}$) were lower than with successful fire perimeter containment ($0.61\ m\ min^{-1}$ $firefighter^{-1}$).

Fireline production rate per aerial resource support

Although no significant differences were observed in grass, meaningful differences were found in shrub (Table 9), in which fireline production rates ranged from $0.51\ m\ min^{-1}$ $firefighter^{-1}$ (without aerial resource support) to $0.63\ m\ min^{-1}$ $firefighter^{-1}$ (with aerial resource support).

The increase of the mean fireline production rates due to aerial resource support was modelled with a logarithmic model (Table 6 and Fig. 3). The coefficient of determination (R^2) is 0.87 and the MAE is $0.09\ m\ min^{-1}$ $firefighter^{-1}$. The variable included in the model was the time between aerial resource drops, which ranged between 3 and 30 min. A short time between aerial resource drops was associated with an increase in firefighting crew production.

Discussion

This study is the first handcrew fireline production rate research that used GPS for data collection during active wildfires in Spain. Despite the difficulties of collecting data in high-pressure operational environments (Plucinski 2019*a*), our assessment of the 204 selected firefighting operations in three study regions provided enough information to mitigate the bias generated in data gathering. The availability of a reliable dataset for estimating the productivity of fire crews fills an important gap in knowledge about fire suppression operation efficiency (Katuwal *et al.* 2016; Thompson *et al.* 2018). The methodological framework presented in this research is very flexible, enabling extrapolation to other territories and fire crew structures. In addition, the utilisation of a database with different fire sizes, from less than 1 to 3000 ha, allowed for a more comprehensive assessment of real fireline production rates of fire crews in Mediterranean wildfires.

Our estimates of handcrew fireline production rates exhibited significant variability similar to previous studies (Haven *et al.* 1982; Hirsch and Martell 1996). According to other authors (Broyles 2011; NWCG 2021), the resulting fireline production rates in direct attack are higher than in indirect attack in all fuel types. The percentage change in productivity between type of attack is 54.02% in grass, between 6.06 and 53.73% in chaparral–shrub, and between 63.63 and 84.9% in timber fuel models. Handcrew fireline production rates decreased in indirect attack owing to the wider and more intense shrub clearing and/or burning out required to create a wider fuel break. In addition, the

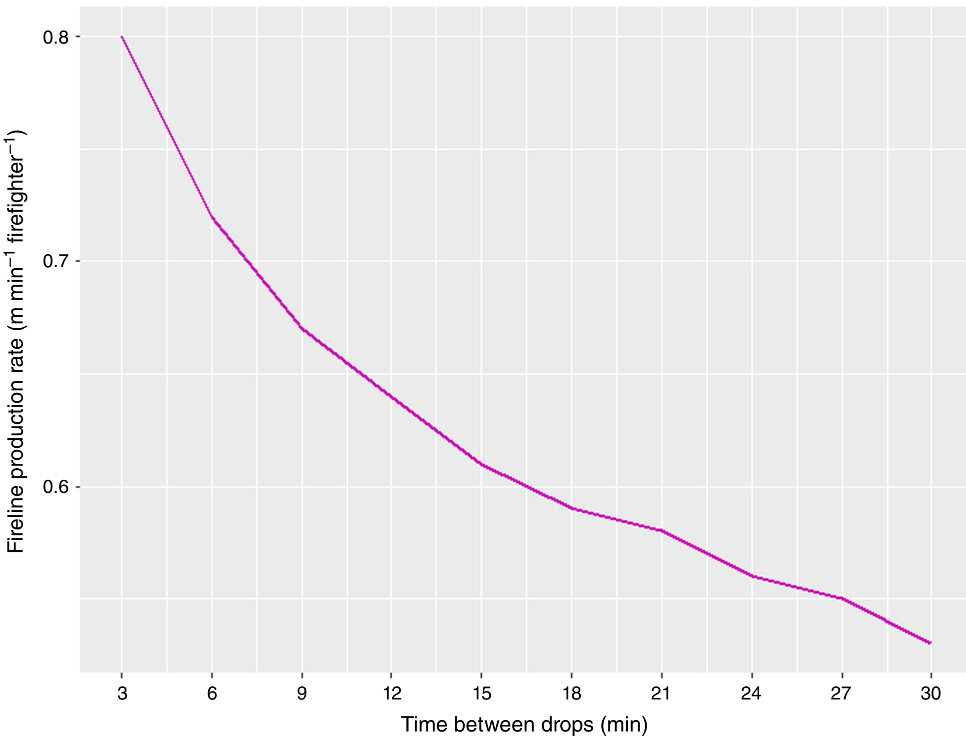

Fig. 3. Handcrew fireline production rate increase due to aerial resource support.

Table 10. Comparative analysis among different studies of fireline production rates in direct attack (m min^{-1} firefighter^{-1}).

Fuel type	Estimated rate (our results)	Broyles (2011)/NWCG (2021)	Jiménez (2014)	Chico (2001)	Chico (1996)
Grass	0.79*–0.87**	0.28	0.92–1.23	1.01–1.44	1.20
Chaparral	0.33	0.11	0.59	0.60	0.74
Shrub	0.51*–0.63**	0.28	0.65–0.83	0.70–0.80	0.80–1.03
Timber understory	0.44	0.18	0.59–0.74	0.56–0.59	0.99
Timber litter	1.06	0.18	0.52	0.71–0.79	0.74–1.23

(*) without aerial resource support, (**) with aerial resource support. Broyles (2011) did not consider aerial resources support. Crews were made up of 20 firefighters. Chico (2001, 1996) considered aerial resources support and crews made up of seven to nine firefighters. Jiménez (2014) used firefighter training data and crews made up of five members.

urgency of constructing a fireline and the pressure of being close to the fire could increase production rates in direct attack (Broyles 2011).

Our results showed that suppression resource productivity varies substantially by fuel type (Table 10). Utilising the Anderson (1982) classification made it possible to appropriately compare our results with other studies. The main differences in production rates during direct attack were observed between chaparral and grass fuel types in previous studies (Chico 1996, 2001; Broyles 2011; Jiménez 2014; NWCG 2021), similarly to the largest difference (69%) observed between chaparral and timber litter in our research. Timber litter has the highest fireline production rate primarily owing to the absence of shrub and tree cutting. Our production rates were lower in grass than in timber litter owing to the presence of the dispersed shrub *Macrochloa tenacissima* L. Kunth. This species presents difficulties for fire suppression due to its high calorific value and flame residence time. Budd 1997 showed production rates from Australian forests higher than our timber litter values.

We observed lower fireline production rates (almost half) than previous Spanish studies (Chico 1996, 2001; Jiménez 2014) in all fuel types except timber litter, and higher (almost three times) than American rates (Broyles 2011; NWCG 2021) in all fuel types (Table 10). On the one hand, the main difference with previous Spanish studies (Chico 1996, 2001) is the working time (shift) of suppression operations, which was longer in our research, likely resulting in more firefighter fatigue. Whereas we considered direct observations on Mediterranean active fires, other studies such as Jiménez (2014) overestimated fireline production rate values considering firefighter training exercises. In active fires, the working demand, thermal stress conditions and smoke inhalation create a more challenging working environment (Rodríguez-Marroyo *et al.* 2011, 2012). Broyles (2011) emphasised the need of field observations by trained observers in order to determine production rates accurately.

The large dissimilarities between our results and the American approaches (Broyles 2011; NWCG 2021) appear related to different crew sizes, not having the same definition of the working time variable, the lack of aerial resource support in American research and a different handline width (0.50 m in Spain versus 1.00 m in the USA). Spanish and American handcrews carry out work on the same basis (digging a handline of bare mineral soil directly along a fire edge or indirectly at some distance from the fire) with a very similar combination of hand tools and work organisation (chainsaws go first cutting the woody material, followed by Pulaskis to cut roots and other material, then hoes to scrape material, and finally, shovels and McLeods to clean up). Broyles (2011) and NWCG (2021) analysed crews of 20 firefighters. Moreover, these authors included rest breaks, and driving and/or hiking in their estimates. Our study included rest breaks but excluded travel time (driving or hiking). Most of the wildfires in Spain are controlled in initial attack and, in this case, handcrews do not complete their daily shift working on them. Consequently, considering effective work without travel time makes more sense in Spanish wildfires. American handcrew fireline production rates are more useful for financial analyses and long-term productivity suppression estimations (extended attack and long-lasting wildfires). However, our results have wider applicability in short-term productivity suppression estimations (initial attack).

Fireline production rates were not significantly different based on weather conditions. However, wind speeds above 50–60 km h^{-1} reduced production rates as they complicated working scenarios and personnel mobility, suggesting some weather differences can occur. Therefore, further efforts should be made in enlarging the range data above this wind speed threshold value (only three registers above this value in our database) as suggested by Holmes and Calkin (2013), who emphasised the importance of considering the reduction in fireline production rates under extreme fire conditions. However, under these weather conditions, wildfires would generally not be able to be suppressed, and, consequently, firefighting could become more complex or even impossible. Regarding other environmental conditions, slope and stoniness were meaningful variables influencing handcrew production rates in previous studies (McCarthy *et al.* 2003; Jiménez 2014). Nevertheless, our findings showed a lack of significance for these. However, as differences of 33.83% were identified between suppression work developed on contour lines and steep slopes, standard values of fireline production rates should distinguish between these, which would be much more representative than a unique value, in a similar way to dozer rates (García-Egido 2015). However, stoniness, expressed by categories, is a highly subjective variable.

Other authors (McCarthy *et al.* 2003; Finney *et al.* 2009; Holmes and Calkin 2013) have highlighted the existence of a discordance between standard fireline production rate values and the real rates in large wildfires. In this sense, production rates were lower in large wildfires, decreasing by 38.81% from small fires (<1 ha) to larger fires (>50 ha). This fact could be related to a higher flame length and fireline intensity exposure, longer working time, accumulation of fatigue and demotivation due to the unsuccessful containment operations.

Fireline production rates decreased by 46% for unsuccessful containment operations in shrub. This is consistent with Broyles (2011), who highlighted that failures in control objectives increase time and cost for fire containment and firefighter unsafety. Other authors (Holmes and Calkin 2013) identified that the production rates were reduced between 14 and 93% when accounting for the percentage of the active fire perimeter contained and environmental conditions.

In agreement with Broyles (2011) and Chico and Poza (2009), our findings show that as the number of firefighters in a crew increases, the production rate decreases (by 51.47% from fire crews of <7 firefighters to >9 firefighters). Further, we found that the most efficient crew is made up of nine firefighters. Adding more members does not lead to improved productivity of individual firefighters. These results are consistent with Broyles (2011), who observed that the optimal number of firefighters constructing lines on Type II and Type II Initial Attack crews was 10. Chico and Poza (2009) found different productivity thresholds depending on fuel model and attack type, agreeing with our findings in grass (seven to nine firefighters). Despite this result, fire agencies usually design crews made up of more than the optimum number. This is due to the final crew size depending on the type of fire and the objective pursued. In large wildfires, larger crews are required to contain larger perimeters in less time even though the individual production rate is reduced.

According to our results, handcrew fireline production rates decreased by 41.79% after 180 min (3 h) of suppression work. Although the maximum time analysed in this study was 605 min (10 h), most of working time recorded data were below 180 min (3 h). The majority of wildland firefighter actions were carried out on small fires (initial attack) where the total workday (daily shift) is not used up. Suppression activities lasting longer than 180 min (3 h) negatively affect productivity owing to accumulated fatigue. This is consistent with Lindquist (1970) and Chico and Poza (2009) who observed significant differences in fireline production rates based on working time. Chico and Poza (2009) also observed different productivity thresholds depending on attack type; as such, after 120 min (2 h) of suppression work in direct attack and 180 min (3 h) of suppression work in indirect attack, handcrew fireline production rates decrease meaningfully.

Aerial resource support increased handcrew fireline production rates in line with other research (Holmes and Calkin 2013; Florec *et al.* 2019). According to our findings, aerial resource support increased fireline production rates between 9.19% (grass) and 19.04% (shrub). Time between aerial resource drops, based on the distance from water reservoirs, influenced handcrew fireline production rates. In line with this, if the time between aerial resource drops is below 5 min, the productivity of handcrews greatly increases (Fig. 3).

Our statistical models demonstrated good fit to the data and high explanatory power within the range of variables tested (Table 1). Further, the working time model is restricted to shrub in direct and indirect attack and the aerial resource support model is limited to helicopter support (excluding other types of aerial resource). Modelling the effect of working time and aerial resource support in handcrew fireline production rates (Table 6) is useful to better adjust the values of productivity to the reality of suppression. Regarding working time, the model could be used to manage crew replacements. Regarding aerial resource support, the model could be used to decide the number of aerial resources needed to work in combination with ground resources. More aerial resources decrease the time between drops and, as has been shown, increase the fireline production rate.

The applied monitoring techniques will provide highly reliable results for the planning of suppression operations. This study reduces uncertainties regarding handcrew fireline production rates by accounting for working conditions and aerial resource support (Thompson and Calkin 2011; Rodríguez y Silva and González-Cabán 2016). The identification of different fireline production rates is important for fire managers (Plucinski 2019*a*). They need to identify the number of resources that are necessary to put the flames out for effective planning of suppression, mainly with simultaneous wildfire occurrences, when the availability of resources is limited and appropriate assessments and prioritisations are needed. Furthermore, uncertainty is highly related to a lack of knowledge regarding the productivity of different combinations of suppression resources. Generally, these resource combinations are determined based on the experience of the incident commander or incident management team. Recent studies (Rodríguez y Silva 2017; Rodríguez y Silva and Hand 2018) have used econometric techniques to generate productivity models based on combined suppression resources. Further studies should be conducted to identify fireline production rates and potential fire containment capability based on environmental and working conditions, and resource combinations. In addition, in a pre-planning approach, changes in fuel models such as fuel treatments cause fuel load reductions and would decrease flame length and suppression difficulty (Rodríguez y Silva *et al.* 2020). Consequently, fireline production rates would increase. Therefore, fire and land managers should introduce this as an essential consideration in their preparedness decision making.

Conclusions

Despite the difficulties in gathering accurate field data on handcrew fireline production rates, this approach provides reliable standard values in Spanish Mediterranean wildfires. Moreover, a comparison was made between research results from Spain and the United States. Our findings show that firefighter productivity is lower in active fires than in simulated or training conditions. Several variables were also identified as statistically significant that influence productivity. Handcrew fireline production rate increases with direct attack, fuel types with low loads, aerial resource support and fire containment success. Meanwhile, handcrew fireline production rate decreases with longer working times, and larger fire and crew sizes. Therefore, the importance of incorporating working condition and psychological variables in handcrew fireline production rate assessment has been highlighted. In addition, the need to make appropriate decisions is justified in terms of firefighter productivity. Inefficient allocation of suppression resources led to poorer fireline production rates.

Knowing the operating capability of suppression resources is the responsibility of fire managers in order to guarantee the safety and effectiveness of suppression. The availability of standard fireline production rates provides a useful tool for fire managers in both preparedness (e.g. fuel break networks design) and at an operational level (to plan suppression strategies and tactics, assigning efficient number, type and combination of suppression resources to wildfires). Furthermore, the evaluation of work effectiveness and resource productivity is the starting point for fire agency optimisations.

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