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Wildland firefighters' thermal exposure in relation to suppression tasks

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Abstract. The main purpose of this study was to characterise the thermal environment and risk of heat burns of wildland firefighters in relation to the suppression tasks performed in real wildland fires. Measurements of air temperature and heat flux were performed by affixing heat flux and ambient temperature sensors on the outer and inner surface of the wildland firefighters' protective garments. Suppression time was divided according to the task performed in direct attack, backfire, mop-up and patrol. These tasks accounted for 95.2 ± 78.4, 103.3 ± 41.7, 80.5 ± 24.8 and 71.3 ± 53.0 min, respectively. Overall, the mean heat flux was higher during backfire (2165 ± 1604 W m^{-2}) than in direct attack (558 ± 344 W m^{-2}), mop-up (371 ± 254 W m^{-2}) and patrol (354 ± 307 W m^{-2}). However, during the direct attack, average and maximum thermal dose was ~94 and ~110 (kW m^{-2})$^{4/3}$ s, respectively. These values are within the threshold of pain and first-degree burns. However, no first-degree burns were reported for the sample. Overall, the thermal exposure measured may be considered light. However, high thermal exposure values may be obtained at specific moments, which may cause first-degree burns in wildland firefighters.

Keywords: wildland fire, heat flux, thermal dose, heat stress, skin burns, thermal environment, firefighters, exposure.

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Introduction

Wildland firefighters have to perform highly demanding physical activities in adverse conditions that are unique to wildland firefighting (Rodríguez-Marroyo *et al.* 2012), which means exposure to high-thermal-load environmental conditions (Budd *et al.* 1997; Cuddy *et al.* 2015) while wearing personal protective equipment (Carballo-Leyenda *et al.* 2017, 2018). The combination of these factors considerably increases heat strain, which can lead to impaired physical performance, heat exhaustion, or even heat stroke (Cuddy and Ruby 2011; Carballo-Leyenda *et al.* 2018).

Specific suppression tasks such as hiking, building firelines, brush removal, fire smothering, or setting backfires (Ruby *et al.* 2002) are performed using different hand tools (e.g. hoes, rakes, axes, chainsaws, backpack pumps, swatters and shovels), and this has been related to increased intensity of effort (Brotherhood *et al.* 1997). The effect of performing such tasks on wildland firefighters' physiological heat strain has previously been studied in real scenarios (Rodríguez-Marroyo *et al.* 2011; Rodríguez-Marroyo *et al.* 2012). It was reported that when suppression work is performed close to flames (i.e. direct attack), the firefighters' thermophysiological response increases owing to the nature of the tasks performed and the ambient temperature (Rodríguez-Marroyo *et al.* 2011). In these scenarios, ambient temperature and heat flux are the factors related to the thermal stress experienced by the user (Lawson 2009). When there are sources of heat emission (e.g. flames) as in firefighting, heat flux analysis can help to fully describe environmental exposure (Bröde *et al.* 2010; Willi *et al.* 2016; Horn *et al.* 2018). In addition, measurement and analysis of the thermal environment could provide information regarding the risk to wildland firefighters (Rossi 2003; Zárate *et al.* 2008; Raimundo and Figueiredo 2009; Butler 2014).

The heat flux released by flames in wildland fires has been widely studied in recent decades owing to its importance in fire behaviour (Albini 1986; Butler *et al.* 2004; Anderson *et al.* 2010; Frankman *et al.* 2010, 2013). Nevertheless, there is a lack of studies analysing the influence heat flux has in the work environment on thermophysiological response (Budd *et al.* 1997; Willi *et al.* 2016) and on the occurrence of heat burn injuries (Butler and Cohen 1998; Rossi 2003; Zárate *et al.* 2008; Butler 2014). Therefore, the present study aimed to characterise the immediate thermal environment of wildland firefighters in relation to the suppression tasks performed in real wildland fire suppression scenarios. The dose of thermal radiation received was then estimated and compared with burn injury probability thresholds for each suppression task analysed.

Methods

Participants

Five male wildland firefighters from different Spanish helitack crew bases voluntarily took part in this study (age: 28 ± 1 years;

body mass: 76.2 ± 0.9 kg, height: 175.5 ± 0.5 cm). Volunteers were recruited from different crews from all work shifts, thus increasing the probability of attending a wildland fire. All had at least 2 years' experience in wildland fire suppression, and a check was made to ensure that they were familiar with live-fire policies and procedures. Written informed consent was obtained from the subjects before starting the study. The experimental protocol was developed in accordance with the guidelines of the Helsinki Conference for research on human subjects and was approved by the Ethics Committee of the University of León, Spain.

Study design

Thirty-eight wildland fires were recorded over four summer seasons (i.e. June–October). The wildland firefighters' local thermal environment was characterised through air temperature and heat flux measurements in each wildfire suppression event they attended. Two heat flux sensors and an air temperature probe were placed on the outer surface of the protective suit and two heat flux sensors were located inside it. The objective of the placement of the heat flow and temperature sensors was 2-fold: (1) the external sensors recorded the heat flux and temperature of the work environment (Willi *et al.* 2016); (2) the internal sensors helped to define the thermal environment inside the protective garment to estimate the thermal dose and probability of injury to firefighters (Raj 2008). To facilitate the placement of sensors and probes, the manufacturer (Confecciones Oroel, La Muela, Zaragoza, Spain) customised 10 protective suits by adding holes, ducts and pockets (Fig. 1). These custom-made modifications allowed the safe placing of sensors and dataloggers inside the suit without restricting the mobility of the firefighters. The adjustments made to the protective clothing complied with the standards for protection against heat and flame for wildland firefighters' personal protective equipment (International Organization for Standardization ISO 16073–1:2019), and they were designed to alter the outer surface of the fabric as little as possible. As a result, the heat protection of the garment was not affected.

When a fire alarm notification was received, the participants put on their personal protective equipment (i.e. helmet, gloves, mid-calf leather boots, goggles and neck shroud), which included the protective suit (65% fire-retardant viscose, 30% Nomex® and 5% Kevlar®) in which the data acquisition system was integrated. Heat flux and ambient temperature were measured continuously (Fig. 2). In this study, only the suppression time, defined as the time span from the beginning of suppression efforts to completion, was analysed; the time taken travelling to or from the fire zone was not considered. The duration of each task was obtained from the official fire report, in which the crew leader compiled the duration of travel to the site, suppression tasks performed and breaks during the deployment. These time intervals were verified with video footage from a portable camera (GoPro-3) in the helmet of the firefighter wearing the measurement equipment. The suppression time was divided according to the task performed into direct attack, backfire, mop-up and patrol. Direct attack involves performing suppression tasks near flames, using hand tools such as fire swatters and water back pumps. Backfire involves setting a fire along the inner edge of a fireline (i.e. >100 m), mainly to consume the fuel in the path of a wildfire or change the direction or force of the convection column of the fire. Mop-up consists of extinguishing or removing burning material along or near the control line to stop the fire spreading, while patrolling is carried out along the perimeter of the fire to control its progress or to prevent a fire starting up again once it has been extinguished. While direct attack requires working near the front flames (i.e. <0.5 m), mop-up and patrolling can be performed at a distance from the live fire (i.e. >100 m). This division of tasks was made taking into account their importance within the total suppression time in the wildland fires selected.

Fig. 1. Heat flux sensors and temperature probe on the outer (*a*), and inner (*b*) surface of the protective suit; (*c*) dataloggers.

Measurements

In this study, we measured the combined radiative and convective heat flux using four thin planar black-coated heat flux sensors (Captec Enterprise, Lille, France; dimensions: 20 × 20 mm; thickness: 0.4 mm; heat flux range: ±50 kW m^{-2}; nominal sensitivity: 3.08–3.82 μV W^{-1} m^{-2}; emissivity of measurement surface ε: 0.97; response time: 300 ms). Heat flux sensors were attached to the internal and external surface of the protective suit, on the left side of the chest and the left thigh (Fig. 1). The internal and external sensors were positioned side by side in parallel so that they did not overlap. All sensors were placed with the measurement surface facing outwards to maximise measurement of the incident heat flux (Raj 2008). The heat flux was recorded continuously at a sampling rate of 5 s (0.2 Hz) from the moment of departure to the return from the fire event. Positive heat flux values were considered as heat gain, while negative values were considered as heat losses. The sensors were connected to a four-channel datalogger (QuadVolt ±100 mV, Madgetech, Warner, NH, USA; nominal range: ±30 kW m^{-2}; resolution: 1.43 W m^{-2}).

The air temperature was measured with a Pt100 resistive temperature probe (ControlTemp, Santa Perpetua de Mogoda, Barcelona, Spain; nominal range: –200 to 650°C; accuracy: ±[0.30 + 0.005 × T]°C; response time t_{90}: 5 s) placed on the left side of the chest of the garment surface. The temperature probe was connected to a specific datalogger (LogBox AA IP65; Novus, Porto Alegre, Brazil; nominal range: –40 to 70°C; accuracy: 0.2% full scale) placed in an inside pocket of the protective suit created for that purpose. The air temperature was continuously measured at a sampling rate of 5 s (0.2 Hz). The effect of flame radiation and solar radiation on the Pt100 probe was not minimised, as it was considered that this temperature would

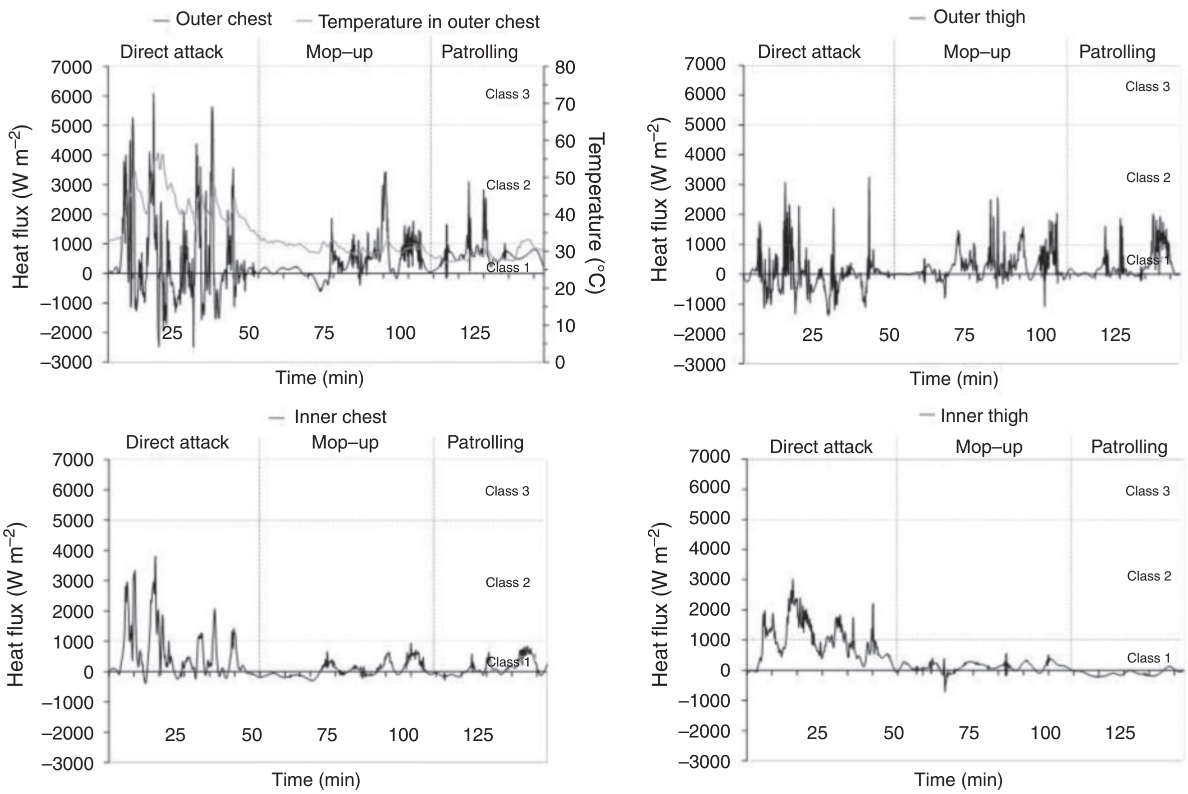

Fig. 2. Heat flux and temperature profile during a representative wildfire. Class 1: heat flux ≤1000 W m^{-2}; Class 2: >1000 to ≤5000 W m^{-2}; Class 3: >5000 to ≤7000 W m^{-2}. The wildland firefighter wearing the data acquisition system performed direct attack, mop-up and patrolling tasks.

reflect the temperature of the work environment more realistically (Foster and Roberts 1994; Rossi 2003; Eglin *et al.* 2004; Willi *et al.* 2016; Horn *et al.* 2018). The environmental temperature was classified by type of task performed (i.e. direct attack, backfire, mop-up and patrol). The ambient temperature in the geographical area of the wildland fire provided by the National Meteorological Agency was compared with the work environment temperature.

Four thermal categories were defined based on the heat flux thresholds previously described for structural firefighters to characterise thermal exposure in terms of risk of injury (Krasny *et al.* 1988; Foster and Roberts 1994; Rossi 2003): Class 1, heat flux ≤1000 W m^{-2}; Class 2, >1000 to ≤5000 W m^{-2}; Class 3, >5000 to ≤7000 W m^{-2}; Class 4, >7000 W m^{-2}. A heat flux of 1000 W m^{-2} corresponds to that received on a summer day and is assumed to be harmless for any exposure time (Raj 2008). A heat flux of 5000 W m^{-2} can cause pain after 15 s and second-degree burns after an exposure of 30 s. There is consensus among several international agencies in considering this threshold as the exposure limit to thermal radiation for people without protection (Raj 2008). When firefighters wear Nomex cloth (210 g m^{-2}), second-degree burns could occur after 90 s at incident radiant heat fluxes of ~7000 W m^{-2} (Butler and Cohen 1998; Zárate *et al.* 2008). Wildland firefighters' thermal protective clothing limits the external heat flux transfer to ~70% (Carballo-Leyenda *et al.* 2019), so we only considered the heat flux recorded in the sensors inside the protective suit to analyse the risk of burn injury. The thermal dosage for each exposure category was calculated using the heat flux and the exposure time recorded in the sensors inside the protective clothing using Eqn 1 (Kinsman 1991; Parsons *et al.* 2014), to estimate the potential burn injury risk for each sensor over time:

$$\mathrm{TDU} = (q_{in})^{4/3} \times t \qquad (1)$$

where TDU is Thermal Dosage Units ([kW $m^{-2}]^{4/3}$ s), q_{in} is incident heat flux (kW m^{-2}) and t is exposure duration (s).

We defined *exposure time* as the periods when sensors registered positive heat flux (i.e. heat gain). The ratio of exposure time to suppression time was then calculated for each sensor and task to ascertain how much of the suppression time involved heat gain. Travelling time to or from the fire area was not included in this calculation.

Statistical analysis

First, quality control of the heat flux data was performed, eliminating from the analysis corrupted data stemming from failure of the data acquisition system, an open circuit pattern or direct loss of the sensor. These issues were identified through graphical representation of the signal since a geometric pattern is observed to indicate an open circuit issue. In the remaining records, the outliers were visually detected and replaced with the

Table 1. Mean and maximum heat flux, exposure time and ratio of exposure time/suppression time during direct attack (mean ± s.d. (range))
*, differences with inner sensor ($P < 0.05$); †, differences with outer chest ($P < 0.05$)

	Heat flux (W m^{-2})	Maximum heat flux (W m^{-2})	Exposure (min)	Exposure time/suppression time (%)
Outer thigh	661 ± 501*	5019 ± 3837*	61.1 ± 38.8*†	46 ± 31*†
	(76–1927)	(577– 11641)	(10.4–178.3)	(3–99)
Inner thigh	326 ± 261	1681 ± 1816	28.5 ± 23.5	21 ± 21
	(48–1371)	(178–9694)	(2.3–84.9)	(1–97)
Outer chest	823 ± 635*	4789 ± 4029*	36.6 ± 27.1*	24 ± 16*
	(31–2507)	(175–11488)	(1.3–108.5)	(2–62)
Inner chest	420 ± 323	2,913.6 ± 3139	20.7 ± 20.6	11 ± 9
	(34–1290)	(133–7110)	(0.2–81.0)	(11–9)
Global average	558 ± 344	3600 ± 2454	36.7 ± 31.8	26 ± 24

Table 2. Mean and maximum heat flux, exposure time and ratio of exposure time/suppression time during backfire (mean ± s.d. (range))

	Heat flux (W m^{-2})	Maximum heat flux (W m^{-2})	Exposure (min)	Exposure time/suppression time (%)
Outer thigh	1231 ± 1145	3907 ± 5096	44.6 ± 26.2	10 ± 6
	(257–2492)	(616–9778)	(18.3–70.6)	(5–16)
Inner thigh	1077 ± 71	2796 ± 2591	26.4 ± 8.0	6 ± 2
	(819–1594)	(294–5388)	(18.2–8.0)	(5–8)
Outer chest	4299 ± 1411	6543 ± 5169	38.0 ± 46.6	9 ± 11
	(2887–5710)	(1374–11712)	(5.5–91.3)	(1–21)
Inner chest	2053 ± 863	4563 ± 4134	34.0 ± 23.5	8 ± 5
	(1555–3050)	(429–5977)	(10.5–57.6)	(3–13)
Global average	2165 ± 1604	4452 ± 3992	35.7 ± 26.0	8 ± 6

average of the values directly before and after them. To reduce the noise still present in the signal, the Wavelet Shrinkage Denoising Method (Donoho and Johnstone 1994) was executed for each of the four heat flux sensor signals. This method has been shown to be more effective at reducing noise than other traditional signal processing methods (e.g. Fourier transforms, moving average filter, Savitzky–Golay filter), since it preserves the original shape characteristics of the signal while improving the signal-to-noise ratio (Yang *et al.* 2009). Following the methodology proposed by Gradolewski and Redlarski (2014), denoising parameters were selected: *Coiflets* wavelets family, with five decomposition levels, *minimax* threshold selection algorithm and *soft thresholding* with *mln* rescaling function. The denoising process was performed with the *wden* function of *MATLAB R18b V.9.5.0* (MathWorks Inc., Natick, MA, USA).

Data were checked for normal distribution using the Shapiro–Wilk test. When normality was not fulfilled, a logarithmic transformation of data was performed. The mean and maximum heat flux, exposure time, exposure to suppression time ratio and thermal dose were compared by a three-way ANOVA with repeated-measures for position (i.e. chest *v.* thigh) and thermal classes (i.e. thermal Class 1, 2 3 and 4) and a between-subject factor for task (i.e. direct attack, backfire, mop-up and patrol). The mean and maximum work environment temperature was analysed using a one-way ANOVA to determine differences between suppression tasks. The assumption of sphericity was checked using Mauchly's test; if this assumption was not met, the Greenhouse–Geisser adjustment of the level of significance was performed. When a significant *F*-value was found, Bonferroni's post-hoc test was used to establish differences between means. Comparison of the environmental temperature in the wildfire area *v.* the temperature in the work environment was made using an independent Student's *t*-test. The results are expressed as mean ± s.d. except where otherwise stated. Values of $P < 0.05$ were considered statistically significant. *SPSS V.22.0* statistical software (SPSS Inc., Chicago, IL, USA) was used.

Results

Of the total wildland fires data sets recorded, only 23 were considered valid and were subsequently analysed. Fifteen wildfires were discarded because the presence of misleading data and failures in the signal were visually verified (i.e. connection with dataloggers and sensors were damaged or lost). Overall, the mean suppression time was 176.3 ± 122.4 min, and the mean and maximum heat fluxes were 827 ± 605 and 3928 ± 3275 W m^{-2}, respectively. The duration of the suppression tasks was similar, 95.2 ± 78.4, 103.3 ± 41.7, 80.5 ± 24.8 and 71.3 ± 53.0 min for direct attack, backfire, mop-up and patrol, respectively.

Tables 1–4 show the external heat flux, exposure time and ratio of exposure to suppression time for each task. Globally, the heat flux was higher ($P < 0.001$) during backfire 2165 ± 1604 W m^{-2} (Table 2) compared with direct attack 558 ± 344 W m^{-2} (Table 1), mop-up 371 ± 254 W m^{-2} (Table 3) and patrol 354 ± 307 W m^{-2} (Table 4).

Table 3. Mean and maximum heat flux, exposure time and ratio of exposure time/suppression time during mop-up (mean ± s.d. (range))
*, differences with inner sensor ($P < 0.05$)

	Heat flux ($W m^{-2}$)	Maximum heat flux ($W m^{-2}$)	Exposure (min)	Exposure time/suppression time (%)
Outer thigh	534 ± 308*	2587 ± 1615*	53.9 ± 31.3	30 ± 25
	(175–1379)	(677–3385)	(13.0–98.1)	(6–80)
Inner thigh	212 ± 127	1257 ± 1199	53.0 ± 26.3	30 ± 24
	(101–282)	(115–1989)	(10.1–93.5)	(5–80)
Outer chest	445 ± 283	2787 ± 2813	44.1 ± 19.3	24 ± 16
	(41–638)	(197–4085)	(18.2–77.8)	(9–57)
Inner chest	293 ± 161	2073 ± 1965	38.6 ± 26.6	20 ± 17
	(30–382)	(97–1918)	(10.2–96.6)	(5–50)
Global average	371 ± 254	2176 ± 2000	47.3 ± 29.4	26 ± 20

Table 4. Mean and maximum heat flux, exposure time and ratio of exposure time/suppression time during the patrol (mean ± s.d. (range))
*, differences with inner sensor ($P < 0.05$)

	Heat flux ($W m^{-2}$)	Maximum heat flux ($W m^{-2}$)	Exposure (min)	Exposure time/suppression time (%)
Outer thigh	691 ± 455*	1880 ± 952	51.7 ± 34.6*	24 ± 13*
	(154–1288)	(742–4861)	(13.6–116.0)	(6–46)
Inner thigh	175 ± 116	758 ± 615	29.9 ± 32.0	14 ± 11
	(55–320)	(157– 4356)	(4.6–107.4)	(1–36)
Outer chest	301 ± 219	1545 ± 1385	32.8 ± 19.5	17 ± 10
	(51–1137)	(132–7856)	(0.8–60.6)	(0–28)
Inner chest	247 ± 143	986 ± 766	22.4 ± 16.9	11 ± 8
	(19–632)	(417–5387)	(1.5–61.6)	(1–27)
Global average	354 ± 307	1292 ± 1023	34.2 ± 27.9	17 ± 11

Comparison of heat flux between tasks showed that when firefighters performed backfiring, chest heat flux was higher ($P < 0.05$) than that recorded in direct attack, mop-up or patrolling. Within-task analysis showed that while performing direct attack, the average heat flux, maximum heat flux and exposure time were significantly higher in the external sensors in both the chest ($P < 0.05$) and the thigh ($P < 0.001$) (Table 1). However, when mop-up and patrolling were performed, significant differences ($P < 0.05$) between the external and internal values of heat flux and exposure time were only found on the thigh.

The area weather temperature at wildland fire locations was significantly lower ($P < 0.05$) than the temperature of the work environment (24.6 ± 8.9 *v.* 32.6 ± 8.9°C), which reached a maximum value of 78.0 ± 8.9°C. The environmental temperatures were similar between suppression tasks (Table 5). However, the maximum ambient temperature was significantly higher ($P < 0.05$) while performing direct attack (73.8 ± 23.7°C) and backfire (80.6 ± 17.3°C) compared with patrol (36.6 ± 5.5°C).

Table 6 shows the variables measured inside the protective suit according to thermal exposure classes and suppression tasks. The values of heat flux obtained within each exposure class were in the lower part of the class interval. Thermal Class 1 had a significantly longer exposure time ($P < 0.05$) compared with exposure durations in thermal Classes 2, 3 or 4. Within each thermal class, no statistical differences were found ($P > 0.05$) between tasks in heat flux, exposure time or thermal dose. The estimated thermal dose reached maximal values during direct attack, with a mean value of 99 ± 20 TDU. Considering the values of heat flux and exposure times in each class, the global weighted average of heat flux for direct attack, backfire, mop-up and patrol was 603 ± 582, 2213 ± 1020, 522 ± 241.6 and 403 ± 238 W m^{-2}, respectively.

Table 5. Mean and maximum work environment temperature (°C) during analysed suppression tasks (mean ± s.d. (range))
*, differences with patrol ($P < 0.05$)

	Mean value	Maximum value
Direct attack	32.3 ± 5.7	73.8 ± 23.7*
	(23.0–42.4)	(35.8–123.0)
Backfire	33.5 ± 2.3	80.6 ± 17.3*
	(32.0–36.0)	(68.2–100.4)
Mop-up	34.3 ± 4.7	54.4 ± 29.7
	(22.0–66.3)	(24.9–99.1)
Patrol	30.3 ± 4.7	36.6 ± 5.5
	(22.3–38.7)	(24.9–42.4)
Global average	32.6 ± 8.9	78.8 ± 23.2
	(22.4–66.3)	(35.8–123.0)

Discussion

These data provide the first time-resolved picture of the thermal environment while performing common suppression tasks of

Table 6. Mean heat flux, exposure time, ratio of exposure time/suppression time and thermal dose inside the protective suit according to the exposure classes (mean ± s.d.)

q, heat flux; *, differences with Class 2 ($P < 0.05$); †, differences with Class 3 ($P < 0.05$); ‡, differences with Class 4 ($P < 0.05$)

		Direct attack	Backfire	Mop-up	Patrol	Average
Class 1 ($q \leq 1000$ W m^{-2})	Heat flux (W m^{-2})	226 ± 145*†‡	152 ± 174	184 ± 131*	175 ± 96*	210 ± 139*†‡
	Exposure time (min)	33 ± 15†‡	13 ± 9	47 ± 36*	28 ± 39*	34 ± 41*†‡
	Exposure/suppression (%)	19 ± 20†‡	3 ± 2	21 ± 43*	22 ± 19*	21 ± 25*†‡
	Thermal dose (kW m^{-2})$^{4/3}$ s	1 ± 1*†‡	1 ± 1	1 ± 0	1 ± 0*	1 ± 1*†‡
	Number of fires	22	3	5	6	
Class 2 ($1000 < q \leq 5000$ W m^{-2})	Heat flux (W m^{-2})	1780 ± 462†‡	2253 ± 169	1527 ± 421	1683 ± 747	1763 ± 484†‡
	Exposure time (min)	11 ± 23	3 ± 1	10 ± 9	1 ± 1	10 ± 21
	Exposure/suppression (%)	6 ± 11	8	4 ± 4	1 ± 1	5 ± 10
	Thermal dose (kW m^{-2})$^{4/3}$ s	12 ± 5†‡	16 ± 1	7 ± 2	11 ± 6	12 ± 5†‡
	Number of fires	9	1	3	3	
Class 3 ($5000 < q \leq 7000$ W m^{-2})	Heat flux (W m^{-2})	5693 ± 371‡	5983.7 ± 421.7			5668 ± 364‡
	Exposure time (min)	1 ± 1	1			1 ± 1
	Exposure/suppression (%)	0 ± 0	0			0 ± 0
	Thermal dose (kW m^{-2})$^{4/3}$ s	51 ± 4‡	51 ± 12			51 ± 4
	Number of fires	8	1			
Class 4 ($q > 7000$ W m^{-2})	Heat flux (W m^{-2})	8871 ± 1397				8871 ± 1398
	Exposure time (min)	2 ± 2				2 ± 2
	Exposure/suppression (%)	1 ± 0				1 ± 0
	Thermal dose (kW m^{-2})$^{4/3}$ s	99 ± 20				99 ± 20
	Number of fires	3				

Spanish wildland firefighters. Our results highlight that in tasks performed near the live-fire front, such as backfiring or direct attack, heat flux may reach intensities capable of causing pain and burn injuries. Nevertheless, the duration of the wildland fires and the variability of exposure contributed to a lower average thermal load in comparison with results in the literature (Budd *et al.* 1997; Rossi 2003; Willi *et al.* 2016). Despite this, environmental exposure may become a net heat gain, which could contribute substantially to increasing wildland firefighters' physiological heat strain (McLellan *et al.* 2013).

The mean ambient temperature (32.6 ± 8.9°C) and heat flux (827 ± 605 W m^{-2}) obtained in this study is slightly higher than the heat load on a clear summer day (Raj 2008). Budd *et al.* (1997) studied environmental heat exposure during the suppression of well-developed experimental wildland fires in Australia. They described a mean environmental temperature of ~29°C and a median radiant heat flux of ~1600 W m^{-2}. Although the mean temperatures analysed in the current study coincide with those analysed by Budd *et al.* (1997), the heat flux was approximately half. Furthermore, our data showed a wider range for both temperature (22–66°C) and heat flux (32–11 800 W m^{-2}) than previously reported values (19–35°C and 700–8600 W m^{-2}) (Budd *et al.* 1997), resulting in less intense and more variable thermal exposure. This fact may be related to methodological differences between the two studies. While Budd *et al.* (1997) carried out prescribed burning where the fuel characteristics, topographic conditions and suppression tactics were homogeneous, our data were recorded in real scenarios characterised by the heterogeneity of wildland fire behaviour. This may lead to high variability in the heat emitted by flames, which affects the suppression task performed by wildland firefighters and the thermal environment to which they are exposed (Zárate *et al.* 2008; Butler 2014).

Some studies have analysed the impact of suppression on the thermal environment in both wildland and structural fires (Zárate *et al.* 2008; Raimundo and Figueiredo 2009; Butler 2014; Horn *et al.* 2018). Suppression is often related to the distance from the flame front, which in turn influences heat flux and the environmental temperatures firefighters are exposed to (Zárate *et al.* 2008; Raimundo and Figueiredo 2009). Our results agree with these observations, as the execution of a direct attack with fire swatters, water back pumps and backfiring leads to a higher heat flux than that recorded during mopping-up or patrolling tasks. In fact, the heat flux received during backfiring was ~4 times higher than during direct attack and ~6 times higher than that found during mop-up and patrol tasks. In this regard, the greater heat flux received during backfire compared with direct attack highlights the different nature of these tasks. During direct attack, the work is performed upwind on the fire front, which may be dealt with by wildland firefighters using hand tools (i.e. flame height <1–1.5 m and fireline intensity <500–1000 kW m^{-1}) (Alexander and De Groot 1988). However, backfire seeks to slow down the fire's progress or reduce its intensity by generating a controlled down-wind fire using the suction effect of the main front (Morvan *et al.* 2013). This means that flames can be taller and therefore emit more heat during backfire (i.e. flame height <2–2.5 m and fireline intensity >2000 kW m^{-1}) (Alexander and De Groot 1988), which would help to explain the greater heat flux received by wildland firefighters under these circumstances. The methodological differences between our study and Budd *et al.* (1997) make it difficult to compare the results according to the type of suppression task. Budd *et al.* (1997) reported the mean heat flux mainly experienced during fire line construction at a distance of ~3 m (1–15 m) from the fire front, where direct attack was only used to deal with spot fires or fireline breaks. In contrast, direct attack and backfire were the main tasks in our study, accounting for ~27 and ~30% of the suppression time, respectively.

Budd *et al.* (1997) reported higher average heat flux, but our data show that the peaks of heat flux attained in wildland fire suppression were more significant than previously described. These maximum values were of the same order of magnitude as those described for structural firefighters in training scenarios (Willi *et al.* 2016) and highlight the significance of spot exposure to the thermal environment, despite a modest mean exposure time. This behaviour may be related to the fact that the main suppression tasks in this study involved working close to flames, so the results would also reflect the natural variation in the heat flux released by the flames (Butler and Cohen 1998).

The measurement method may have influenced the results obtained. In our study, sensors were placed on firefighters' personal protective equipment and the whole wildfire suppression event was recorded. However, previous studies (Budd *et al.* 1997) employed static sensors placed in the working area for heat flux and ambient temperature measurements. Several studies on the environmental conditions in structural firefighting have suggested that the thermal exposure reported through sensors held in fixed positions during firefighting training is not reliable (Eglin *et al.* 2004; Willi *et al.* 2016). This implies that changes to the thermal environment near the firefighters, or to their protective clothing, are not taken into account (Eglin *et al.* 2004; Willi *et al.* 2016). This would be linked to the movement of firefighters towards less intense exposure areas, which would facilitate cooling (Willi *et al.* 2016). This work pattern has also been observed during the suppression of real wildland fires (Rodríguez-Marroyo *et al.* 2011). Wildland firefighters regulate their exposure to heat by taking small breaks away from the fire to reduce the thermal load and exercise intensity (Budd *et al.* 1997; Rodríguez-Marroyo *et al.* 2011).

The environmental work temperature (Table 5) followed the same pattern found in the heat flux measurements. The average environmental temperature reached moderate values (32.6 ± 8.9°C) and was similar between tasks. However, significantly higher environmental temperatures were reached at specific moments while performing direct attack and backfire, mirroring the heat flux pattern. Rodríguez-Marroyo *et al.* (2011) reported similar average environmental temperatures when they analysed the thermal environment according to the type of attack performed by wildland firefighters. In the latter study, the maximum ambient temperature recorded during direct attack was 37.8 ± 2.7°C, which was significantly lower than that obtained in the present work (73.8 ± 23.7°C). This difference may reflect the lower sensitivity of the temperature sensor used in the study of Rodríguez-Marroyo *et al.* (2011) compared with the Pt100, and the fact that it was placed at hip height instead of on the firefighter's chest. Furthermore, the maximum environmental temperature obtained was similar to the mean temperatures reported for structural firefighting in training scenarios (Rossi 2003; Willi *et al.* 2016). This result underlines the lower temperatures that wildland firefighters endure compared with structural firefighters. One of the factors that may underlie this is that wildland fires occur in an open environment, where the energy released by the flames is quickly dispersed in the atmosphere (Arnaldos Viger *et al.* 2004). However, structural firefighting is mainly carried out in closed spaces, which increases the environmental thermal load (Horn *et al.* 2018).

The heat flux values obtained inside the protective suit (Table 6) correlate with the external heat flux behaviour. Our data show that the lowest thermal exposure class (i.e. $q < 1000$ W m^{-2}) was predominant in all the tasks analysed. However, the heat flux reached the highest intensities during direct attack and backfiring, with peak values as high as ~9000 and ~6000 W m^{-2}, respectively. With this in mind, it is not surprising that the highest thermal radiation dosage was reached during direct attack (mean and maximum values of 99 and 110 TDU, respectively) despite the fact that the average heat flux was higher during backfiring (Table 2). Previous studies have correlated thermal radiation dosage within the range of 86–103 and 80–130 TDU with the onset of pain and first-degree burns, respectively (O'Sullivan and Jagger 2004). Therefore, participants may have experienced this level of harm while working near the fire front. However, in the sampled fires, the occurrence of burns was not reported, which could be related to shielding from the impinging heat flux provided by underwear. The sensors were placed inside the protective suit but above underwear, which may have reduced the incident heat reaching the surface of the skin, thus minimising the risk of burns (Raj 2008; Song *et al.* 2011).

The present study is a first step towards determining the net heat load that the thermal environment adds to wildland firefighters' thermal balance. This external load, added to metabolic heat production, would increase the sweat rate to compensate in the heat balance, exacerbating the thermal and cardiovascular strain experienced by wildland firefighters (Bruce-Low *et al.* 2007; Bröde *et al.* 2010). To obtain the net body heat content in this scenario, heat losses through evaporation, radiation and convection should be taken into account. Budd *et al.* (1997) obtained the net heat gain of wildland firefighters by computing body heat gains and losses during experimental fires. These authors reported an increase in the sweat rate from 793 to 1027 g h^{-1} to compensate for a net increase of 216 W in the environmental heat load (i.e. ~115 W m^{-2}). Considering that the mean heat flux obtained in our study (~826 W m^{-2}) would correspond to a net environmental heat gain through radiation and convection and the data obtained by Budd *et al.* (1997), we can speculate that the subjects' sweat rate would reach values of ~1700 g h^{-1}. Sweat rates of ~2000 g h^{-1} have previously been reported in wildland firefighters (Apud *et al.* 2002; Hendrie *et al.* 1997) and structural firefighters (Horn *et al.* 2012). However, such a sweat rate may only be maintained for short periods (<1 h) in acclimated and well-hydrated subjects (Cheuvront *et al.* 2010). The latter highlights the influence that the thermal work environment and hydration status may have on wildland firefighter performance.

To our knowledge, this study is the first to analyse the environmental temperature and the heat flux conditions encountered by firefighters during real wildland fires using a mobile data acquisition system. We approached the comprehensive definition of this complex problem in two steps in an attempt to simplify the analysis of human heat transfer in real scenarios. The first step was to define how much heat they received during fire suppression in order to determine the impact the environment had on the firefighter. This procedure meant that the negative heat flux recorded was not taken into account for the definition of the thermal environment. However, these data can be useful for understanding the potential heat loss from the firefighter to the surroundings that may aid cooling. Neglecting the negative values may lead to overprediction in heat flux assessment and the risk of burn injury using the thermal dosage equation (Wieczorek and Dembsey 2001). The effective suppression time did not account for travel to and from the fire area, as we considered that the most intense thermal exposure conditions would occur during the suppression time. Nevertheless, these data have provided some useful insights into increased metabolic heat generation while moving towards suppression, and how heat is dissipated after suppression while moving away. Finally, thermal dosage calculation allowed us to estimate the consequences of thermal exposure in terms of pain or first-degree burns in a fairly simple manner. However, this simplified equation does not take into account parameters such as initial skin temperature and other biologically relevant heat transfer mechanisms (e.g. sweat, skin perfusion), which may affect the time to pain or first-degree burns (Wieczorek and Dembsey 2001).

These limitations mean that the results obtained cannot be generalised, as our study is an initial approach that should be followed by a more in-depth analysis of a complex phenomenon. Future studies should undertake an in-depth review of the problem, accounting for heat gains and losses to define heat transfer comprehensively. In this regard, correlations between the thermal environment during wildfire suppression with some of the parameters of fire behaviour such as flame size, fireline intensity or distance to flames will help obtain a more precise picture of the situation.

In conclusion, thermal exposure during backfires was more intense than that analysed during direct attack, mopping-up or patrolling tasks. However, the highest values of thermal exposure were reached while performing direct attack. Therefore, activities during direct attack would be more likely to reach heat flux values capable of producing first-degree burn injuries.

Conflicts of interest

The authors declare no conflicts of interest.

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