



Hydrological impacts of a wildfire in a Boreal region: The Västmanland fire 2014 (Sweden)

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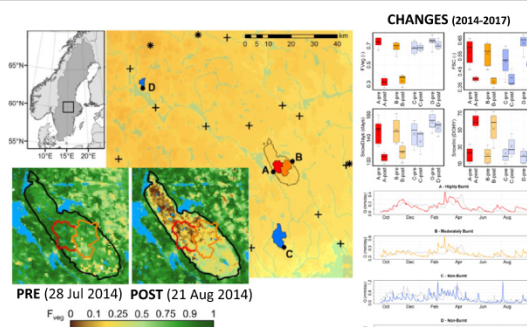
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HIGHLIGHTS

- Shorter and later beginning of snow season in burnt areas
- Change in consecutive conditions, peaked as less disperse flow, in burnt areas.
- Higher flashiness from rainfall-events in late summer
- Combination of in situ streamflow and EO product in reference and burnt sites
- Pilot study of hydrological effects of the Swedish' large wildfire on the Boreal forest

GRAPHICAL ABSTRACT



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ABSTRACT

The largest forest wildfire in Swedish modern history burnt 14,000 ha of Boreal forest in the Västmanland County (south-central Sweden) during the summer of 2014. Here, we assess the impacts of this wildfire on the hydrological regime during the three years after it happened. In the empirical experiment carried out, four catchments (two burnt and two non-burnt nearby) with similar character and climate and with mean area of 20 km² were compared. A total of 23 descriptors accounting for climate, land cover and flow signatures were defined and evaluated before and after the wildfire, using both remote sensing products and in situ streamflow observations. The results show three main changes in the hydrological behaviour of the burnt areas: (i) variation in duration and timing of snow season, with shorter and later beginning of the season; (ii) more dynamic behaviour of the streamflow, with smaller variation coefficient, a reduction in duration of high and low flows conditions and a more oscillating pattern; and, (iii) variations in catchment response (flashiness, runoff coefficient and actual evapotranspiration) from rainfall-events mainly during summer, but also in late autumn. The study also reflects the usefulness of the combined analysis of flow signatures and remote sensing products to detect changes in catchment hydrology.

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1. Introduction

Forest wildfire effects on catchment hydrology are important for scientific understanding of hydrological process changes, interactions, and

societal preparedness for indirect consequences after wildfires. There is a substantial body of literature on hydrologic effects of wildfires (e.g. Moody and Martin, 2001a; Onda et al., 2008; Gleason and Nolin, 2016; Havel et al., 2018). Some of these works study forest wildfire effects on catchment hydrology (Seibert et al., 2010) although, to our knowledge, these effects at catchment scale have not yet been explicitly evaluated using various sources of empirical data. Here, we combine remote

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sensing and hydrologic data pre- and post-wildfire to interpret the broad scale impacts of forest wildfire on the hydrological regime, using two burnt and two reference catchments from a recent large wildfire in Sweden, Northern Europe; with the overall aim of exploring what changes on hydrology we can expect from wildfires in Boreal forests.

Hydrological processes at the watershed scale are highly conditioned by the land cover in the basin (e.g. Blöschl et al., 2007; Hall et al., 2014). Therefore, changes in land cover distribution have an impact on water and energy budgets (Bronstert et al., 2002; Scanlon et al., 2005; Cassiani et al., 2015) and can be seen as an opportunity for better hydrological understanding (Seibert and van Meerveld, 2016). Forest wildfires are alterations that may drastically change land cover across watersheds (Aldersley et al., 2011). After a wildfire, canopy water storage capacity changes (Calder, 2005; Qazi et al., 2017). Hence, the first direct consequence is a modification in interception and volume of precipitation reaching the ground (Madduma Bandara, 1974; Crockford and Richardson, 2000; Jeffery et al., 2014). Other alterations include different partitioning in evaporation fluxes from vegetation and soil (Gerrits et al., 2010; Wang-Erlandsson et al., 2014) and changes in soil moisture dynamics (Silva et al., 2006; Liancourt et al., 2012; van der Ent et al., 2014; Boer-Euser et al., 2016). Also, higher runoff coefficients are commonly observed, which have direct implications in the erosion capacity (Cerdeira and Robichaud, 2009) and the consequent problems related with water quality due to an increasing number of suspended sediments (i.e. soil, burnt tree remains, ashes) (Löfgren et al., 2009; Smith et al., 2011). In general higher concentration of nitrogen and phosphorous (Mast and Clow, 2008; Ferreira et al., 2005), chloride, sulphate and sodium (Murphy et al., 2006), organic carbon (Baird et al., 1999), cyanide (Barber et al., 2003) and some hydrocarbons generated during combustion (Kim et al., 2003), have been observed after wildfires. These substances in contact with the water may be a source of contamination, directly conditioned by local conditions after the wildfire (i.e. hydrometeorology, burnt vegetation type and catchment physiography (Smith et al., 2011). Snow accumulation and melting dynamics can also be affected if the burnt area is located in a snow dominated region, like the Boreal forest (Faria et al., 2000; Gleason et al., 2013; Micheletty et al., 2014). After the wildfire, snowpack is more exposed to solar radiation and snow albedo may be lower due to darkening of the surface from burnt forest remains (Burles and Boon, 2011; Gleason and Nolin, 2016).

Almost all these hydrological impacts are conditioned by the spatial scale (Blöschl and Sivapalan, 1995). At the plot scales all the referred hydrological changes are clearly observed (Beeson et al., 2001; Woods and Balfour, 2008; Ebel et al., 2012; Stoof et al., 2012; Harpold et al., 2014). Nevertheless, a direct extrapolation of these consequences at larger scales, like catchment and regional, may introduce an overestimation in the expected changes. These scales can filter, mix, smooth or dilute these variations (Cammaraat, 2002; Bracken and Croke, 2007; Hallema et al., 2018). To monitor land cover changes at these larger scales, remote sensing products constitute the best option: not only to detect areal changes (e.g. Huete et al., 2010; Hall and Riggs, 2016) but also as an excellent information to complement the in situ streamflow measurements at the watershed outlet.

Furthermore, wildfires have been less common in high latitude regions due to the wetter conditions, snow coverage and Boreal forest structures over these areas. Therefore, a lack of studies is found in this area in comparison to warmer ones (Hulbert, 1969; Lavabre et al., 1993; Moody and Martin, 2001a; Onda et al., 2008; Micheletty et al., 2014). Despite global burnt area declined by about 25% over the period 1998–2015, in Boreal forest a stronger positive relationship between population and wildfire affected area was found for Eurasia and North America (Andela et al., 2017). Namely, in Boreal Russia, more wildfires occurred in years during which the weather was anomalous in the Boreal Russia (Mollicone et al., 2006); however, more than 87% of them were directly caused by humans. In eastern Canada, it was also showed that wildfire frequency increased (Scholze et al., 2006). Despite this increase in frequency in some northern regions, nuclear changes are shown yet in Swedish Boreal forest.

In this context, the objectives of this study are two: first to evaluate the landcover changes due to the wildfire, and second to understand and quantify the effects of these changes on the hydrological regime. Meteorological information, streamflow observations and remote sensing products are used to define different indicators to account for these changes.

2. Study site and data

The studied wildfire burnt an area of 14,000 ha during the summer of 2014 in the Västmanland County, south-central Sweden. It was active for 18 days, from the 31st of July till the 17th of August. The 3.5 °C above the average mean temperature during the beginning of the summer and the 25% below-average precipitation for an average July, favoured the expansion of the wildfire, which was enkindled by a vehicle performing subsoiling. The affected area was mainly covered by the characteristic vegetation of the southern Boreal forest: coniferous needle-leaved evergreen trees (mainly Scots Pine (*P. sylvestris*), but stands of Norway spruce (*P. abies*)), shrubs tolerant to shading and carpets of Boreal forest mosses (Bodin and Nohrstedt, 2016; Lidskog and Sjödin, 2016). The well-drained mineral soil present in the area was almost removed after wildfire and the shallow rocky outcropped in all the area (Bohlin et al., 2017; see Fig. A1 in the Appendix).

Four gauged catchments, with similar physiographic characteristics (i.e. size, altitudes, slopes), original land cover and climatic conditions were selected to assess the possible changes caused by the wildfire (Table 1). Two catchment were located in the burnt area (catchments A and B, in red and orange respectively in Fig. 1); and the other two catchments were outside the burnt area, but situated nearby - within 50 km (catchments C and D, in blue in Fig. 1). These non-burnt catchments were used as reference sites to evaluate that changes were not caused by natural climate variability of the system.

Meteorological data, Earth Observations (EO) products and in-situ streamflow measurements were used as the three main sources of information.

First, the meteorological data used belong to the national database, PTHBV at the Swedish Meteorological and Hydrological Institute (SMHI) (Johansson, 2000). PTHBV is a gridded precipitation and temperature product which uses meteorological stations across Sweden

Table 1
Topographic and land cover descriptors of the studied catchments and availability of discharge measurements at their outlets.

Gauge station name	Gauge station ID	Catchment status	Area (km ²)	Mean elevation (m a.s.l.)	Mean slope* (%)	Forest area (%)	Monitored time series of daily water discharge
Vallsjöbäcken	A	Burnt	17.7	105	6.0	94	1979-01-01 – 2001-01-08 2014-11-12 – 2017-09-30
Gärsjöbäcken	B	Burnt	22.5	109	3.2	80	2014-09-10 – 2016-10-05
Svenbybäcken	C	Reference	36.5	56	2.3	71	1980-08-31 – 2017-09-30
Finntorget	D	Reference	7.0	259	8.6	86	1979-09-04 – 2017-09-30

* Calculated using the digital elevation model (DEM) GSD Terrain elevation databank (50x50m) from Lantmäteriet (cadastral and land registration Swedish authority); and defined as the average value of slope in each DEM cell within the catchment.

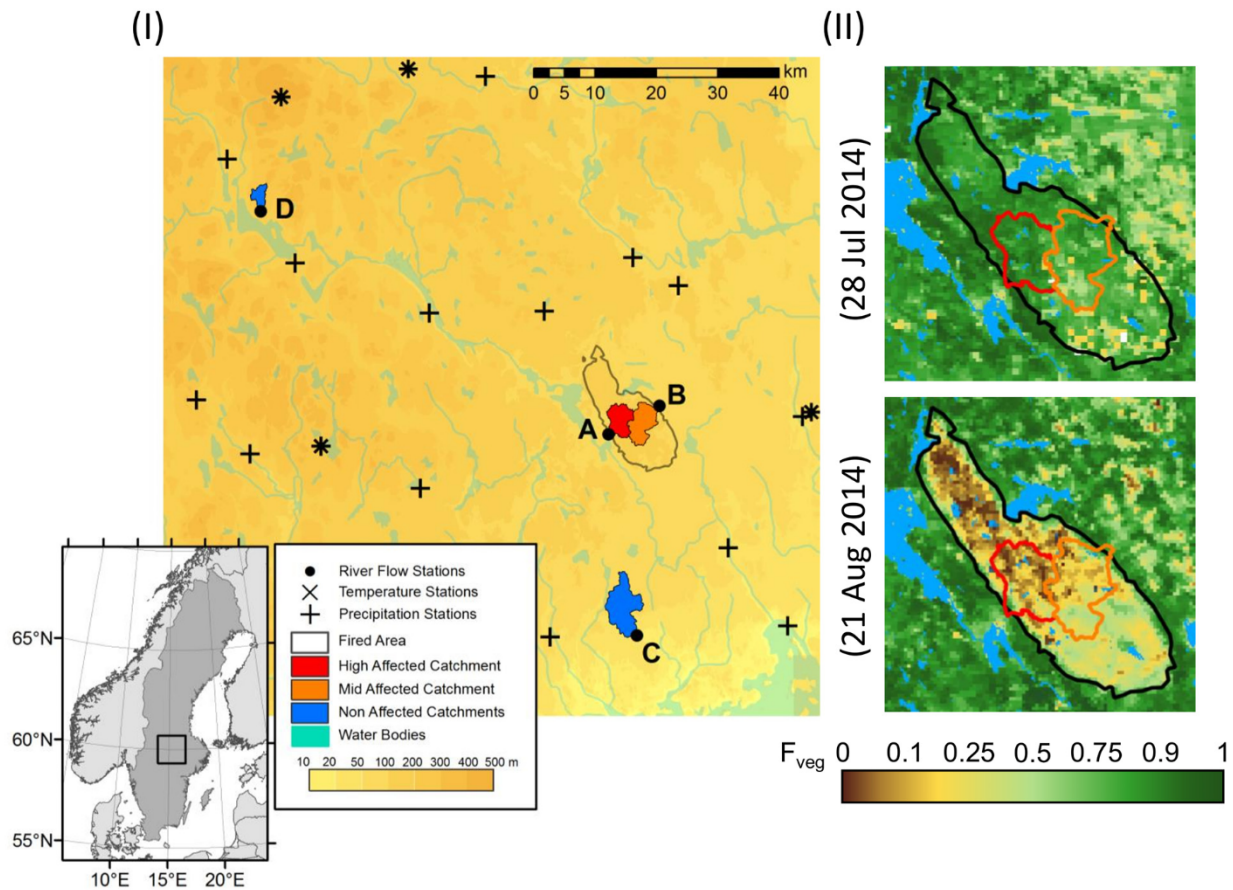


Fig. 1. (a) Location of the Västmanland fire (black line) and the 4 small study catchments (in red, catchment A, highly burnt by the wildfire; in orange catchment B, moderately burnt by the wildfire; in blue, catchments C and D, reference site non-burnt by the wildfire). Locations of the gauging stations for stream flow (black dots) and precipitation (black x) and temperature (black asterisk *). (b) Fractional vegetation cover, before (20/07/2014; upper panel) and after (21/08/2014; lower panel) the wildfire derived from MODIS vegetation product.

(about 700 stations) to derive a grid using interpolation techniques that combine the interpolated variables with other such as altitude, slope, land cover, wind direction or radiation (Johansson and Chen, 2003, 2005). Four of the temperature stations and eighteen of the precipitation stations used to produce this product are located within the study area (black x for temperature and black + for precipitation in Fig. 1).

Second, EO products for vegetation and snow from MODIS were used. The MODIS/Terra (MOD13Q1) and the MODIS/Aqua (MYD13Q1) version 006 (Didan, 2015a, 2015b) were chosen to assess the changes in vegetation canopy due to the wildfire. Both products have a spatial resolution of 250 m and the combined use of both allows increasing temporal resolution from 16-days to 8-days (Table 2). Normalized Difference Vegetation Index (NDVI; Tucker, 1979) is the vegetation index selected from the options provided by the MODIS vegetation product.

Fractional Vegetation Cover (FVeg) before (28/07/2014) and after (21/08/2014) the wildfire has been derived from NDVI following Gutman and Ignatov (1998) to evaluate wildfire severity, which was calculated as the percentage of change in vegetated cover area before and after the wildfire. Wildfire severity differs between the two selected

catchments (Fig. 1.II; Table 3): wildfire effects in Catchment A produced a bigger removal of vegetation than in Catchment B, 84% versus 58%. Therefore, we will refer to Catchment A as highly burnt (in red), and Catchment B as moderately burnt (in orange).

The MODIS/Terra Snow Cover (MOD10A2) version 006 (Hall and Riggs, 2016) was used to evaluate snow dynamics (Table 2). MOD10A2 provides maximum snow cover extension in an 8 days temporal windows at 500 m spatial resolution derived from the Normalized Difference Snow Index (NDSI; Dozier, 1989).

Third, streamflow observations at the studied catchments' outlets were used. In three of the analyzed catchments, gauging stations belong to the SMHI national monitoring network and were operational before the wildfire (A, C and D catchments). In these stations, mean daily streamflow was derived from 15 min water level measurements transformed into discharge using a site-specific calibrated rating curve. On the contrary, observations in catchment B begins after the wildfire. The Swedish University of Agricultural Sciences (SLU) installed a gauging station, which measures streamflow from changes in pressure between water and a reference on land measured using Doppler

Table 2

Summary of Earth Observation (EO) products used in the study. Spatiotemporal resolution, available dates and the number of scenes/dates analyzed (the wildfire was located between two of the MODIS tiles, which sometimes did not have the same availability, for this reason the table makes a difference between them).

Land cover	Product/version	Spatial res. (m)	Temp. Res. (days)	Available period	Number dates analyzed (tile name)
Vegetation	MOD13Q1/006	250	16	2002-01-01 – 2017-09-14	364 (h18v03) – 358 (h18v02)
	MYD13Q1/006	250	16	2002-07-04 – 2017-06-18	334 (h18v03) – 350 (h18v02)
Snow	MOD10A2/006	500	8	2000-02-18 – 2017-09-30	805 (h18v03) – 807 (h18v02)

Table 3

Severity of the wildfire in the whole burnt area and in each of the two selected burnt catchments.

	FVeg before Wildfire (–)	FVeg after Wildfire (–)	Change in FVeg (%)	Severity
Whole burnt area	0.712	0.353	50	–
Catchment A	0.776	0.123	84	High
Catchment B	0.678	0.284	58	Mid

technology. Gaps in observational time series (Table 1) were filled using streamflow simulations from the S-HYPE model (Lindström et al., 2010; Strömqvist et al., 2012), which is the national multi-basin model system for Sweden. Specific model performance analysis was carried out for evaluating the ability to reproduce streamflow in the catchments with continuous observation (see Fig. A2 in the Appendix).

3. Methodology

Hydrological changes in the four selected catchments were analyzed regarding: a) natural climate variability; b) land cover; and c) characteristic flow signatures; during two periods: before (2000–10–01 to 2014–09–30) and after (2014–10–01 to 2017–09–30) the wildfire. The analysis was performed using 23 descriptors that were thought

to account for these three aspects (Table 4). Two climate descriptors (Prec and Tem) were used to validate that the non-burnt reference sites were representing undisturbed conditions for the burnt catchments, assuring that the analysis were not biased by natural variability (Brown et al., 2005). Five descriptors account for land cover changes, in both vegetation and snow, using the previously described EO products for deriving vegetation and snow fractions. Besides, three additional snow related variables (i.e. beginning, ending and duration of the snow season) complete the descriptors in this category. Sixteen streamflow signatures, which characterize different shapes of the flow regimes, were defined based on the suggested metrics by Olden and Poff (2003) and Kuentz et al. (2017). Climate and land cover descriptors were aggregated at catchment scale and flow signatures computed at the outlet of each catchment (Table 4).

Changes were evaluated in several ways. First, temporal changes at annual, and/or monthly scales, depending on the descriptor definition during pre- and post-wildfire periods, were compared using descriptors distributions. Second, spatial changes were analyzed. Differences between burnt and reference sites were compared to establish which changes could be attributed to the wildfire. Finally, visual inspection of temporal seasonal evolution was performed only for the main descriptors in each category: precipitation (Prec), temperature (Temp), fractional vegetation cover (FVeg), fractional snow cover (FSC) and mean daily flow between the pre- and post-wildfire periods.

Table 4

Definition of the descriptors used to evaluate the hydrological changes over the wildfire area, regarding a) climate, b) land cover and c) flow signatures.

Descriptor		Variable	Units	Description	Data source	
Climate						
		Prec	mm	annual/monthly precipitation	PTHBV	
		Tem	°C	annual/monthly mean of mean daily temperature	PTHBV	
Land cover						
Vegetation		FVeg	–	annual/monthly mean of the 8-days Fractional Vegetation Cover (Gutman and Ignatov, 1998)	MOD13Q1/006 MYD13Q1/006	
Snow	Magnitude	FSC	–	annual/monthly mean of the 8-days Fractional Snow Cover	MOD10A2/006	
	Duration	SnowIni	day hydrological year (DOHY)	beginning of the snow season, defined as the first day of the hydrological year with more that 10% FSC in the catchment.	MOD10A2/006	
		SnowEnd	day hydrological year (DOHY)	ending of the snow season, defined as the first day of the hydrological year with less than 10% FSC in the catchment	MOD10A2/006	
		SnowDays	d	number of days between the beginning and ending of the snow season	MOD10A2/006	
Flow signatures						
Magnitude of flow events	Average flow conditions	Skew	–	annual/monthly skewness = mean of daily flows divided by median of daily flows	Streamflow	
		Qsp	mm d ^{−1}	annual/monthly mean of daily flow	Streamflow	
		CVQ	–	annual/monthly coef variation = SD/mean daily flow	Streamflow	
	Low flow conditions	BFI	–	Baseflow Index: mean of 7-days minimum daily flow within a year divided by mean annual daily flow	Streamflow	
		Q5	mm d ^{−1}	annual/monthly 5th percentile of daily flow	Streamflow	
	High flow conditions	HFD	–	annual/monthly High Flow Discharge: 90th percentile of daily flow divided by median daily flow	Streamflow	
		Q95	mm d ^{−1}	annual/monthly 95th percentile of daily flow	Streamflow	
	Frequency events of flow	Low flow conditions	LowFr	–	number of days below 5% of annual mean daily flow divided by the number of days within a year	Streamflow
		High flow conditions	HighFr	–	coef variation in daily low flows (daily flows below the annual 75th percentile of daily flows)	Streamflow
Duration of the flow events	Low flow conditions	LowDurVar	–	coef variation in daily low flows (daily flows below the annual 25th percentile of daily flows)	Streamflow	
	High flow conditions	Mean30dMax	–	mean of 30-day maximum daily flow within a year divided by median annual daily flow	Streamflow	
Timing of flow events		Const	–	annual constancy of daily flow (Colwell, 1974)	Streamflow	
Rate of change in flow events		Rev	–	annual number of reversals (change in the sign in the day-to-day change time series)	Streamflow	
		RBFlash	–	annual/monthly Richard – Baker flashiness: sum of absolute values of day-to-day changes in daily flow divided by the sum of all daily flows	Streamflow	
Catchment response		RunoffCo	–	annual/monthly runoff coefficient: ratio between mean daily flow and mean daily precipitation at annual/monthly scales	Streamflow	
		ActET	mm d ^{−1}	annual/monthly actual evapotranspiration: daily mean precipitation minus daily mean flow at annual/monthly scales	Streamflow & PTHBV	

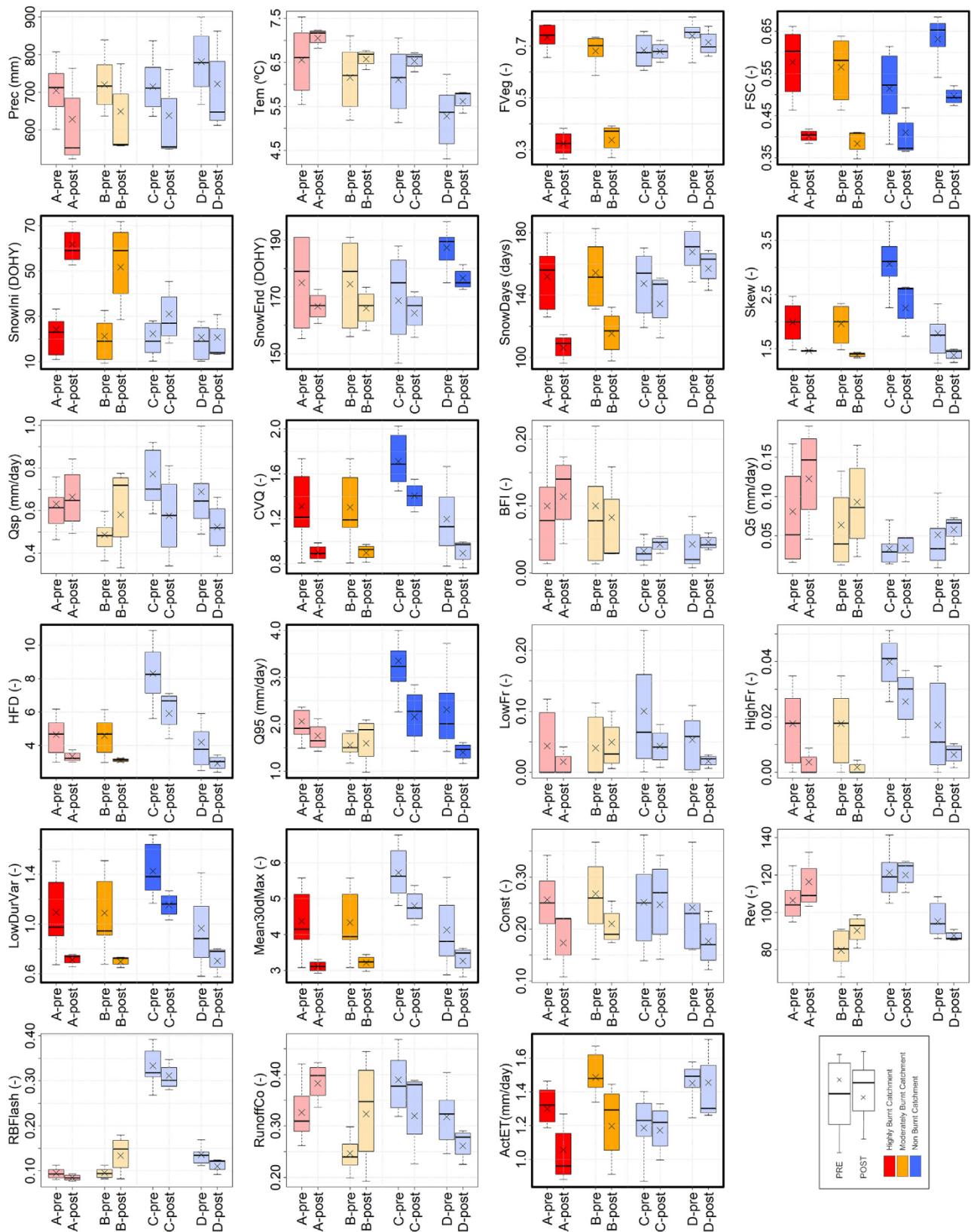


Fig. 2. Distribution of annual values of the 23 descriptors for the pre- and post-wildfire periods in each of the four selected catchments. The box shows 50% of the data (interquartile range), whiskers refer to percentiles 10th and 90th, solid line represents the median value and x the mean value (in total 17 samples, 14 and 3 in the pre- and post-wildfire periods respectively). Red boxes represent the highly burnt catchment, orange boxes the moderately burnt catchment and blue boxes the non-burnt catchments.

Table 5

Changes in mean values descriptors between pre- and post- wildfire periods for each of the four study catchments (in italic descriptor with temporal significant changes and in bold those that in addition show significant variations between catchments).

	Absolute (Post-Fire – Pre-Fire)				Relative ((Post-Fire – Pre-Fire) / Pre-Fire) · 100			
	A	B	C	D	A	B	C	D
Climate								
Prec	–76.53	–71.13	–76.71	–58.99	–10.9	–9.9	–10.7	–7.5
Temp	0.49	0.42	0.42	0.34	7.5	6.8	6.8	6.4
Land cover								
Fveg	–0.41	–0.34	0	–0.02	–55.9	–50.5	–0.6	–3.2
FSC	–0.18	–0.18	–0.11	–0.14	–30.3	–32	–20.4	–21.4
SnowIni	37.45	30.45	8.64	–0.05	154.7	143.6	38.7	–0.2
SnowEnd	–8.33	–8.5	–4.38	–10.69	–4.8	–4.9	–2.6	–5.7
SnowDays	–45.79	–38.95	–13.02	–10.64	–30.2	–25.2	–8.8	–6.3
Flow signatures								
Skew	–0.53	–0.58	–0.81	–0.4	–26.4	–29.4	–26.5	–22.5
Qsp	0.03	0.09	–0.2	–0.17	5.2	19.3	–25.4	–24
CVQ	–0.41	–0.4	–0.31	–0.3	–31.2	–31	–17.8	–25.3
BFI	0.01	–0.02	0.01	0	14	–17	30.3	7
Q5	0.04	0.03	0	0.01	50.6	45.3	2.9	13.7
HFD	–1.29	–1.46	–2.4	–1.26	–27.8	–31.9	–28.9	–30
Q95	–0.31	0.04	–1.19	–0.91	–14.9	2.4	–35.6	–39.4
LowFr	–0.03	0.01	–0.06	–0.04	–60.5	22.5	–57	–66
HighFr	–0.01	–0.02	–0.01	–0.01	–77.8	–88.9	–35	–64.7
LowDurVar	–0.38	–0.39	–0.27	–0.26	–34.9	–36	–19.2	–27.1
Mean30dMax	–1.26	–1.12	–0.92	–0.86	–28.7	–25.8	–16.1	–20.9
Const	–0.08	–0.06	0	–0.06	–32.4	–21.6	–1.6	–26.6
Rev	9.9	10.62	–1.29	–7.48	9.3	13.3	–1.1	–7.9
RBFflash	–0.01	0.04	–0.02	–0.03	–10.5	39.6	–6.3	–19.1
RunoffCo	0.06	0.08	–0.07	–0.06	17.5	30.8	–17.7	–17.9
ActET	–0.24	–0.29	–0.01	0	–18.7	–19.4	–1.2	0.3

4. Results

Temporal changes in each catchment were significant, with no overlapping of interquartile ranges in descriptor distribution before and after the wildfire, for 12 of the defined descriptors at the annual scale (FVeg, FSC, SnowIni, SnowEnd, SnowDays, Skew, CVQ, HDF, Q95, LowDurVar, Mean30dMax, ActET) (see highlighted panels in Fig. 2). All these descriptors, except for SnowEnd, Skew and HDF, showed considerable differences between burnt and non-burnt catchments (Table 5). Moreover, when looking at the monthly scale these changes were only observed for specific months, but different ones depending on the descriptors. The seasonality of the changes allow linking these variations to specific

hydrometeorological processes and conditions that are more determining during these specific periods, such as initial snowfalls in late autumn, high peaks in streamflow during the melting season or heavy precipitation events during summer.

4.1. Natural climate variability

Climate descriptors show variability between the two analyzed periods, which reflects the natural fluctuation in climate throughout the years (Table 5 and Fig. 2).

Annual precipitation was about 70 mm lower in the period after the wildfire, mainly due to a precipitation reduction during December (30 mm) and June (25 mm) (Fig. A3 and Fig. 3). These changes were

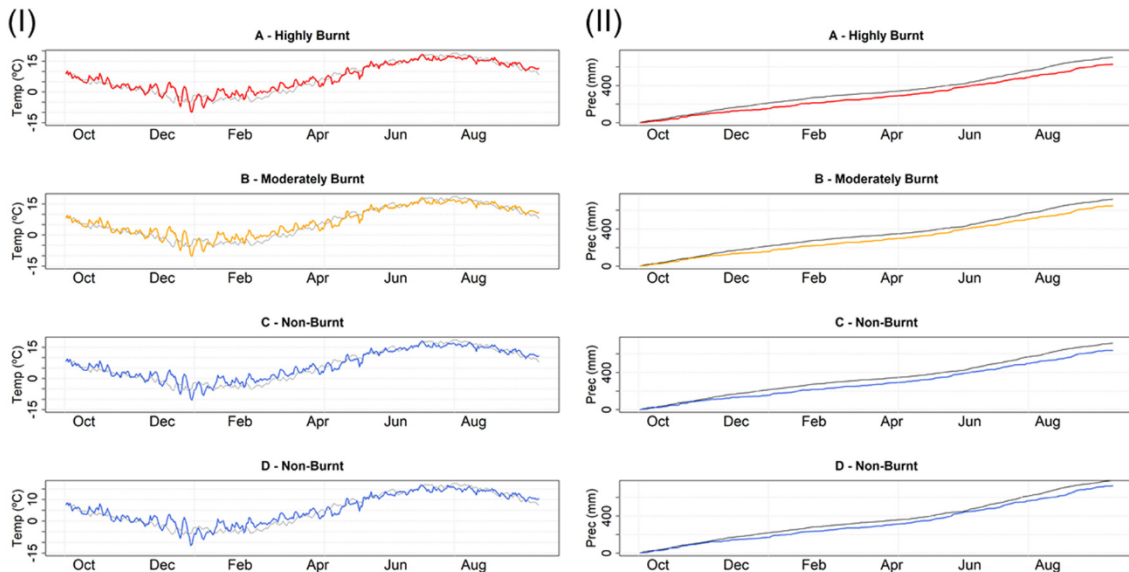


Fig. 3. Seasonal variation of climate variables: (a) mean daily temperature (left panel) and (b) annual cumulative daily precipitation (right panel) for pre-wildfire (grey lines) and post-wildfire (coloured lines) periods in each of the four catchments.

observed similarly in all four catchments with similar relative values of the differences ranging from -7.5 to -10.9% .

Regarding temperature, mean daily temperature on the annual scale showed an increase of about 0.4°C during the analyzed years after the wildfire (Fig. 2). This was mainly attributed to milder autumn and winter seasons, from September to March (Fig. A3). Moreover, this positive change helped to balance the little colder springs and summers found after the wildfire. Again, the same temperature variations were detected in both burnt and reference catchments, with relative differences ranging from 6.4 to 7.5% .

Therefore, these results support the premise of climate cannot be considered as the dominant driving factor to explain the differences between burnt and reference sites. In addition to that, they illustrate the importance of considering climate variability in comparative studies to avoid making actual hydrological change with climate variations.

4.2. Shifts in land cover

Vegetation EO products helped not only to identify the radical land cover change after the wildfire but also the vegetation recovery during the following years (Fig. 4, left panel). Although a fully recovery was not found three years after the wildfire, satellite products showed that about 50% of the burnt area has some type of vegetation; with values of the vegetation fractional cover for catchment A of 0.42 (0.75 in the pre-wildfire period) and for catchment B of 0.44 (0.69 in the pre-wildfire period). The new vegetation type cannot be directly captured by satellite; however, some field campaigns showed that some isolated pine trees, small shrubs, and carpet of mosses are growing in the burnt area. (Fig. A1). As expected, no changes in vegetation were found in the non-burnt reference sites (relative differences lower than 3.5% ; Table 5). The results also clearly identified the duration of the season with active vegetation cover (April to September).

Regarding snow, EO products have allowed us to clearly identify the duration of snow season, which ranges from October to April. All catchments showed a reduction of the mean snow fractional cover in the post-fire period, (Table 5 and Fig. 4, right panel). However, this reduction increases for the burnt catchments with relative differences about 30% versus 20% in the non-burnt catchments. Moreover, and although the mean duration of the snow season during the post-wildfire period was shorter in all studied sites (46 , 39 , 13 and 10 days for catchments A, B, C and D respectively), the changes were more than three times higher in the burnt catchments. This is a consequence of the shift in

onset of the snow accumulation, which change 37 and 30 days (for A and B respectively) for the beginning of the snow season. This effect is not seen in the reference site and thus, it cannot be caused by higher temperatures but rather by the loss of forest canopy (Fig. 2, boxplot Fveg). No significant changes are found for the end date of the snow season.

4.3. Impact on flow signatures

Flow signatures helped us to assess wildfire impact on different streamflow features. Regarding magnitude of the average flows (Q_{sp}), despite the distributions of mean streamflow were within the same variation range before and after the wildfire for each of the study catchments, the sign of the change was different in burnt and reference sites. Namely, this change was positive in burnt site, with an increase of 5.2 and 19.3% in catchments A and B; and negative in non-burnt sites, with a decreasing value of -25.4 and -24% in catchments C and D. This difference between sites was the main cause of the significant change in variation coefficient (CVQ) between burnt and non-burnt sites, with relative differences of -31% and -21% , respectively. Flow skewness (skew) showed a decreasing pattern in all catchments, with more similar values between mean and median streamflow. However, in this case, the changes were similar in all study catchments and therefore non directly attributed to the wildfire (Table 5). In relation to the magnitude of low flow conditions, low flows (Q_5) experienced an increase in all catchments for the period after the wildfire. The change was higher in burnt areas (relative differences of 50.6 , 45.3 , 2.9 and 13.7% for catchments A, B, C and D, respectively), however, the distributions of the values were within the variation ranges observed before the wildfire (Fig. 2). Contrasting, the magnitude of high flows (Q_{95}) showed a general decrease, which was significant in the non-burnt sites (relative differences of -14.9 , 2.4 , -35.6 and -39.4% for catchments A, B, C and D, respectively). Regarding flow frequency and timing, none of the descriptors (LowFr, HighFr and Const) showed any remarkable change. Nevertheless, the differences in the duration of streamflow extreme events were significant, with shorter duration periods of both low and high flow conditions (see LowDurVar and Mean30Max in Fig. 2 and Table 5). All previous findings were in line with the considerably higher number of reversal (Rev) found in the burnt catchments (relative differences of 9.9 , 10.6 , -1.3 and -7.5% for catchments A, B, C and D, respectively). Therefore, the wildfire produced a more dynamic behaviour of the streamflow, with slightly higher mean values

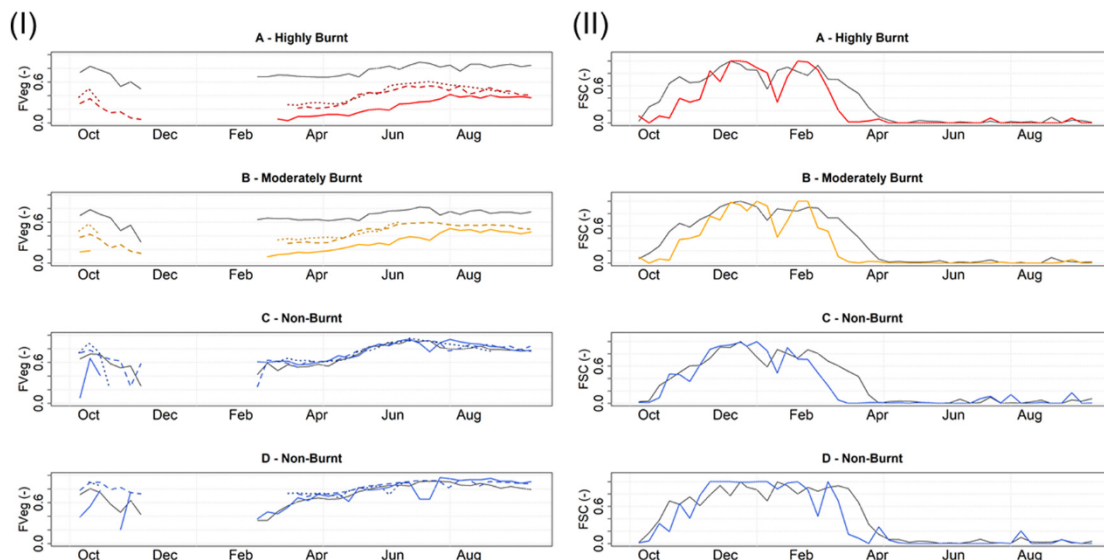


Fig. 4. Seasonal variation of land cover descriptors: (a) daily fractional vegetation area (left panel) and (b) daily fractional snow cover (right panel) for pre-wildfire (grey lines) and post-wildfire (coloured lines) periods in each of the four catchments.

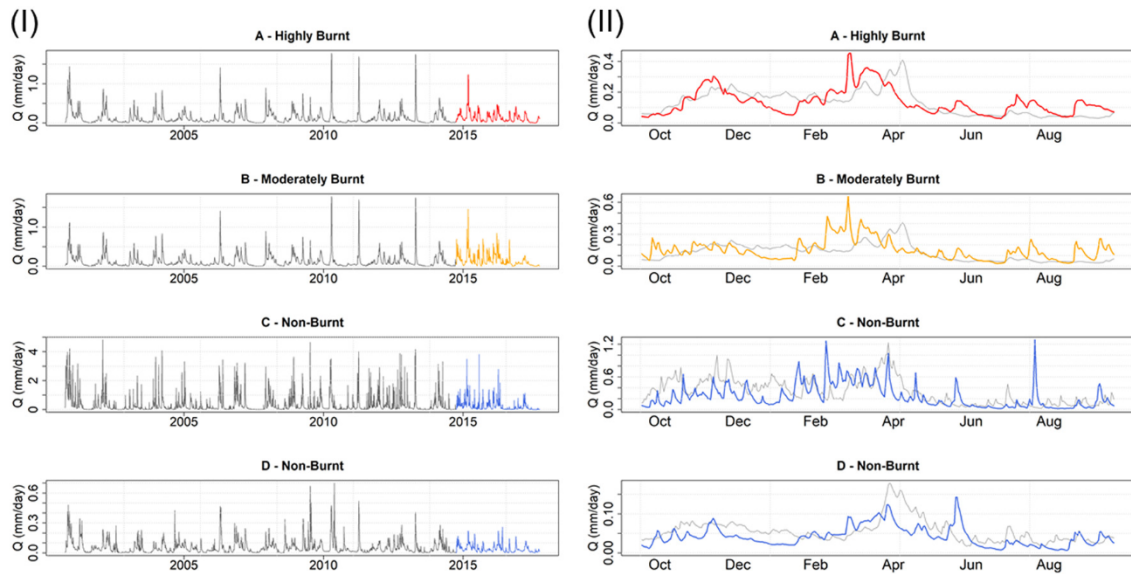


Fig. 5. (a) Temporal evolution (left panel) and (b) Seasonal variation (right panel) of daily flow for pre-wildfire (grey lines) and post-wildfire (coloured lines) periods in each of the four catchments.

translated into smaller variation coefficient, a reduction in duration of high and low flows conditions and a more oscillating pattern.

In relation to streamflow seasonality, the spring peak of streamflow, which is directly linked to the melting of the snowpack, occurred about one month (33 days in average for the two sites) earlier in the burnt sites after the wildfire. However, this change was not seen in the reference sites (Fig. 5 right panel). Analysing changes in specific months, a significant increase in flashiness (RBFlash) was found in the burnt catchments in November. This change was linked with the delay of the accumulation of snow. In December, a decrease was also found in evaporation (ActET), which was only significant in the burnt areas. The general decrease in all catchments can be explained by the significant reduction of precipitation registered during this month. In addition to that, the significance in the burnt areas could be a consequence of the higher peaks in November which unbalance streamflow in relation to the reference catchments. No further remarkable differences were found during late winter and spring. It is in summer when differences in mean streamflow were observed in burnt catchments. Significant changes with higher skewness, variation coefficient and flashiness were showed in August. In September, the changes were significant for extreme flows (Q5, Q95) and flashiness (RBFlash). The combination of a wetter summer with the lower interception storage capacity after vegetation canopy removal, as well as, lower soil capacity to retain water due to loss of soil during the wildfire event, are probably two main factors controlling these changes during the summer period.

5. Discussion

Three main changes in the hydrological regimen were identified after the wildfire: (i) variation in duration and timing of snow season; (ii) change in flow dynamics conditions, with smaller variation coefficient, a reduction in duration of high and low flows conditions and a more oscillating pattern; and, (iii) variations in catchment response (flashiness, runoff coefficient and actual evapotranspiration) from rainfall-events mainly during summer, but also in late autumn. These changes may be attributed to variations in some hydrological drivers over the burnt catchments, mainly a different partitioning of precipitation due to a lower interception, which may result in a different magnitude of the water and energy fluxes generated before and after the wildfire (Fig. 6). All these changes have a strong seasonal component,

where snow storage is primarily affected during late autumn, winter and early spring and the soil storage during late spring and summer (Figs. A3–A6).

The reduction of duration in the snow season was a direct consequence of the wildfire. The loss of forest canopy modified the snow interception by reducing the amount of snow stored by the canopy. Hence, snow was no longer kept in the tree crowns but directly reached the ground, with a consequence modification of the effective snowfall (Fig. 6). Although the remained dead branches could store some snow, these amounts are often negligible compared to those accumulated in non-burnt Boreal forest (e.g. Hedstrom and Pomeroy, 1998). According to Pomeroy and Schmidt (1993), the total canopy snow interception in Boreal forest can reach 60% of the total snowfall and it can be translated into a total sublimation loss component than can reach 30–40% of the total intercepted snow. These proportions changed after the wildfire with larger amounts of snow reaching the ground. However, the higher exposition to solar radiation (Gary, 1974) and wind (Link and Marks, 1999) made the snowpack melting rate quicker, and shortened the duration of the season. In addition, the charred forest remains, which dirtied the snowpack, may also have contributed to this change of melting rates. Lower snow albedo is specifically important in the first snow season after the wildfire (Gleason et al., 2013). Similar reduction was showed in the first snow after a wildfire in other areas worldwide, with mean reduction of 7.5 over the Sierra Nevada Mountains in California (Micheletty et al., 2014) and 23 days in a sub-alpine forest in Oregon (Gleason et al., 2013). However, in the Västmanland wildfire this reduction seems to be more accentuated, with a mean short of 42 days. This difference could be explained by its location at higher latitude than the other study areas, which could make it more sensitive to changes in longwave radiation due to general lack of daylight during winter (Sicart et al., 2006). Moreover, the trend observed in the second and third years after the wildfire points to closer values to those observed in the reference sites for the same period.

Regarding changes in flow dynamic conditions, it is known that wildfires alter interception, infiltration, and evapotranspiration dynamics (Nolan et al., 2014; Desilets et al., 2007; Anderson et al., 1976). Previous studies in a Boreal forest nearby our study area (about 200 km to the east of the Västmanland wildfire) quantified the water stored in the canopy by interception up to 20–30% of the total water balance (Grelle et al., 1999). Without the tree canopy, this interception capacity is negligible. But not only interception is affected, also evapotranspiration

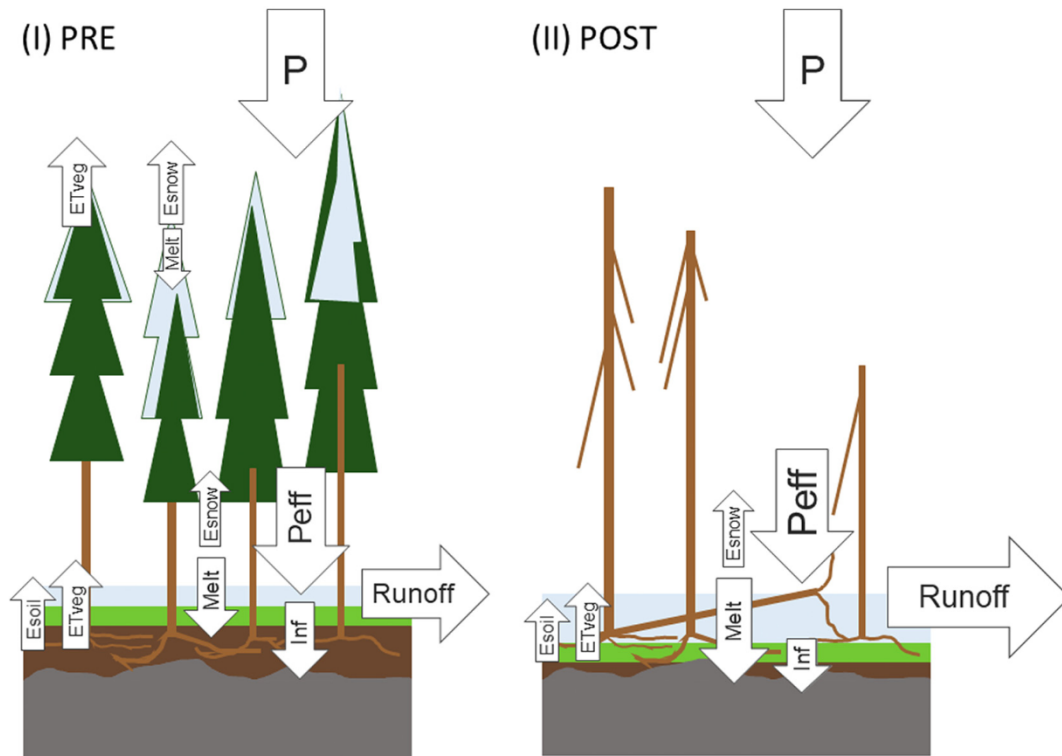


Fig. 6. Conceptual scheme of water storages and fluxes in the system (a) pre and (b) post the wildfire. The size of the arrows indicates the magnitude of the flux in the system.

from the canopy, which the same study quantifies as 85% of the total evapotranspiration. The other 15% of evapotranspiration would correspond to evaporation from the soil, which after the wildfire was almost removed (see Fig. A1 bottom panels in the Appendix) and thus its capacity to store and evaporate water. Soil losses were mainly a consequence of soil structure collapse produced by the high temperatures reached during the wildfire. It was interesting enough that despite this a priori higher water availability to produce runoff and maybe more extreme events in river discharges as usually observed in other studies world-wide (e.g. Lavabre et al. (1993) in France, Montes-Helu et al. (2009) in eastern USA, and Nolan et al. (2014) in Australia; and Evans et al. (1999) in Australia, Inbar et al. (1998) in Israel and Moody and Martin (2001b) in western USA), the general streamflow behaviour was reflected in more oscillating flow but without big extremes. The constant character of the precipitation during autumn and spring favoured this more homogeneous response of the flow. Moreover, the presence of snow made that during snow season water available was dampened by the snowpack regardless of the magnitude of the precipitation events. However, the quicker melting rates in burnt sites due to a higher exposition to solar radiation and wind, not only shifted the peak of streamflow consequence of final spring melting, but also altered the melting dynamics during the snow season. This fact has been especially significant at the beginning of the snow season, when variation in flashiness was found due to a quicker accumulation and melting dynamics in shallow snowpacks. It was only during the summer, with higher precipitation intensities when magnitude and intensity of higher streamflow were significant as expected.

As a final remark, it should be recognized that the findings in this empirical study are dependent on the data availability. Therefore, the results may be affected by discrepancy in time-series duration and gaps. Nevertheless, there are other inherent data uncertainty (e.g. the different instruments used in the flow gauging stations and the common error associated to them, the possible smoothed interpolation of the weather, or the uncertainty in the algorithm used in deriving EO

products) that has not been assessed in this study but can also influence our findings. Moreover, it should be noted that overall, the detected impact on hydrology from wildfires is rather small compared to other changes on going changes, specially river regulation (Arheimer et al., 2017). Arheimer and Lindström (2019) stated that regulation of river flow has the largest impact on the hydrological regime, reducing spring floods with up to 100% and increasing winter flow by several orders of magnitude. On the contrary climate changed the total river flow up to 20% and tree removal by wildfires and storms has minor impacts at medium and large scales.

6. Conclusions

This study proves that wildfires impact Boreal hydrology, and therefore, it can be considered as pilot study to identify and tackle its consequences extrapolating the local effects on the hydrological regime to other Boreal areas. The main findings of this study can be summarized:

- Water fluxes (interception, effective precipitation, infiltration, evapotranspiration, ablation) have been modified by the wildfire, not only by changes in the capacity of snow, vegetation, and soil storages to retain water but also altering their previous partitioning.
- The loss of tree canopy has changed previous infiltration, interception, evapotranspiration, and snow patterns; not only modifying the capacity of soil, vegetation and snow to retain water, but also altering the water fluxes between them, with different significance depending on variables and temporal scales studied.
- Hydrological changes on the annual scale were found in relation to snow season duration, shorter and with a later beginning. In addition, more dynamic behaviour of the streamflow, with slightly higher mean values translated into smaller variation coefficient, a reduction in duration of high and low flows conditions

and a more oscillating pattern were detected in the burnt catchments. On the seasonal scale the main significant changes were found in summer, with higher and flashy streamflow events in the burnt catchments.

- The comparison of burnt and non-burnt catchments has proven to be efficient to separate wildfire impact in the hydrological regime from natural climate variability. Moreover, the use of flow signatures has allowed differentiating streamflow behaviour further than a simple time-series analysis. Finally, using of EO products has added an extra value to the study, since it has helped not only in the mapping of the burnt areas and their severity, but also to evaluate vegetation recovery and snow influence. Three years after the wildfire half of the area has recovered some type of vegetation.

CRediT authorship contribution statement

Rafael Pimentel: Conceptualization, Methodology, Software, Formal analysis, Data Curation, Writing – Original Draft, Visualization; Berit

Arheimer: Conceptualization, Methodology, Writing – Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A



Fig. A1. Example of the new vegetation appearing after the Västmanland wildfire (four upper photos) and soil losses (two bottom photos).

The model performance for the study sites was evaluated for each of the defined flow signatures (Table 4) concluding that only significant changes between model and observations appear for the signature on annual number of reversals, defined as the number of changes in the sign in the day-to-day time series during the year (Rev).

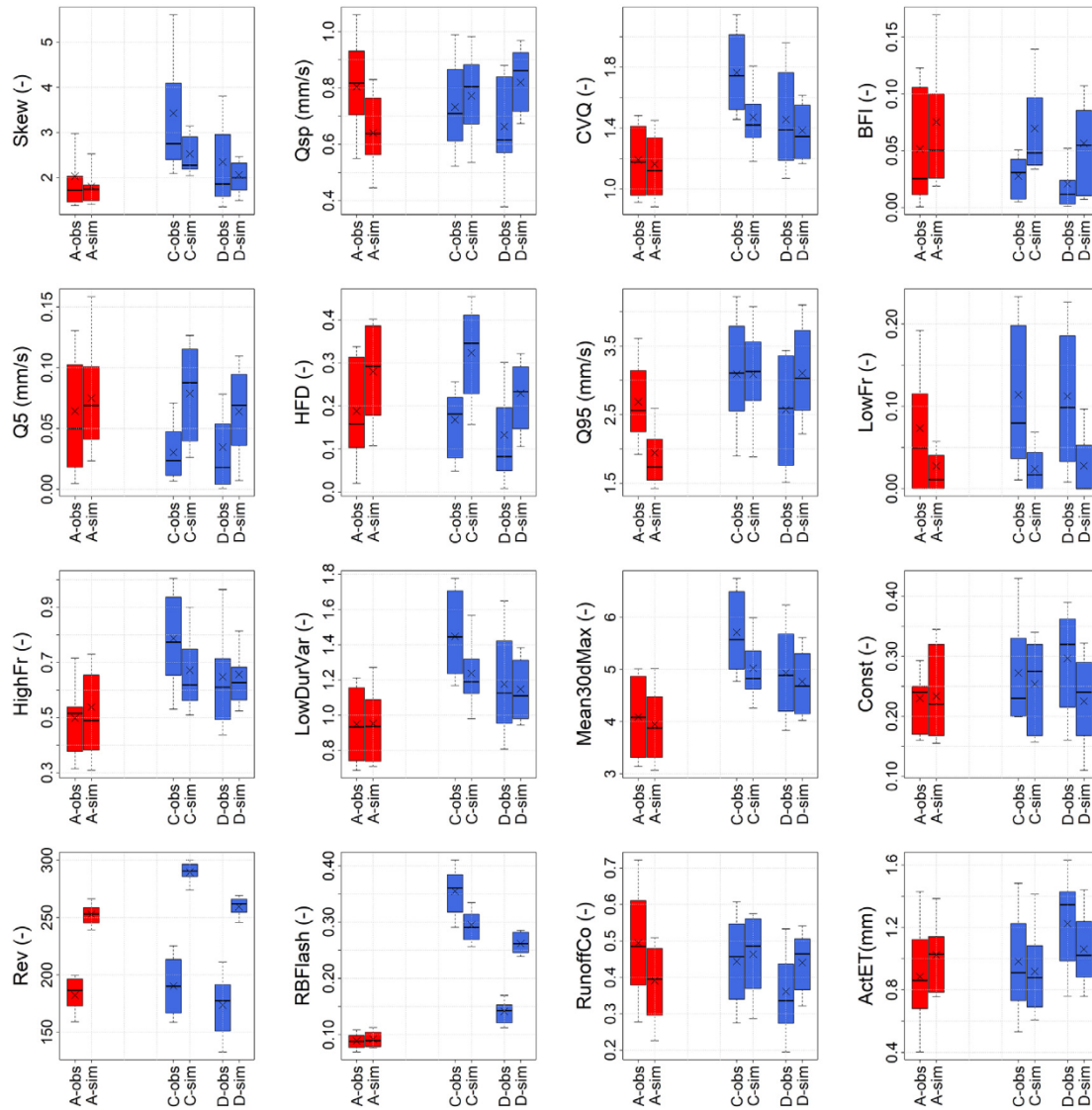


Fig. A2. Annual distribution of the 16 flow signatures for observation (Table 2) and simulated (S-HYPE) values in each of the four selected sites. Red box highly burnt site; orange box moderately burnt site and blue boxes, non-burnt.

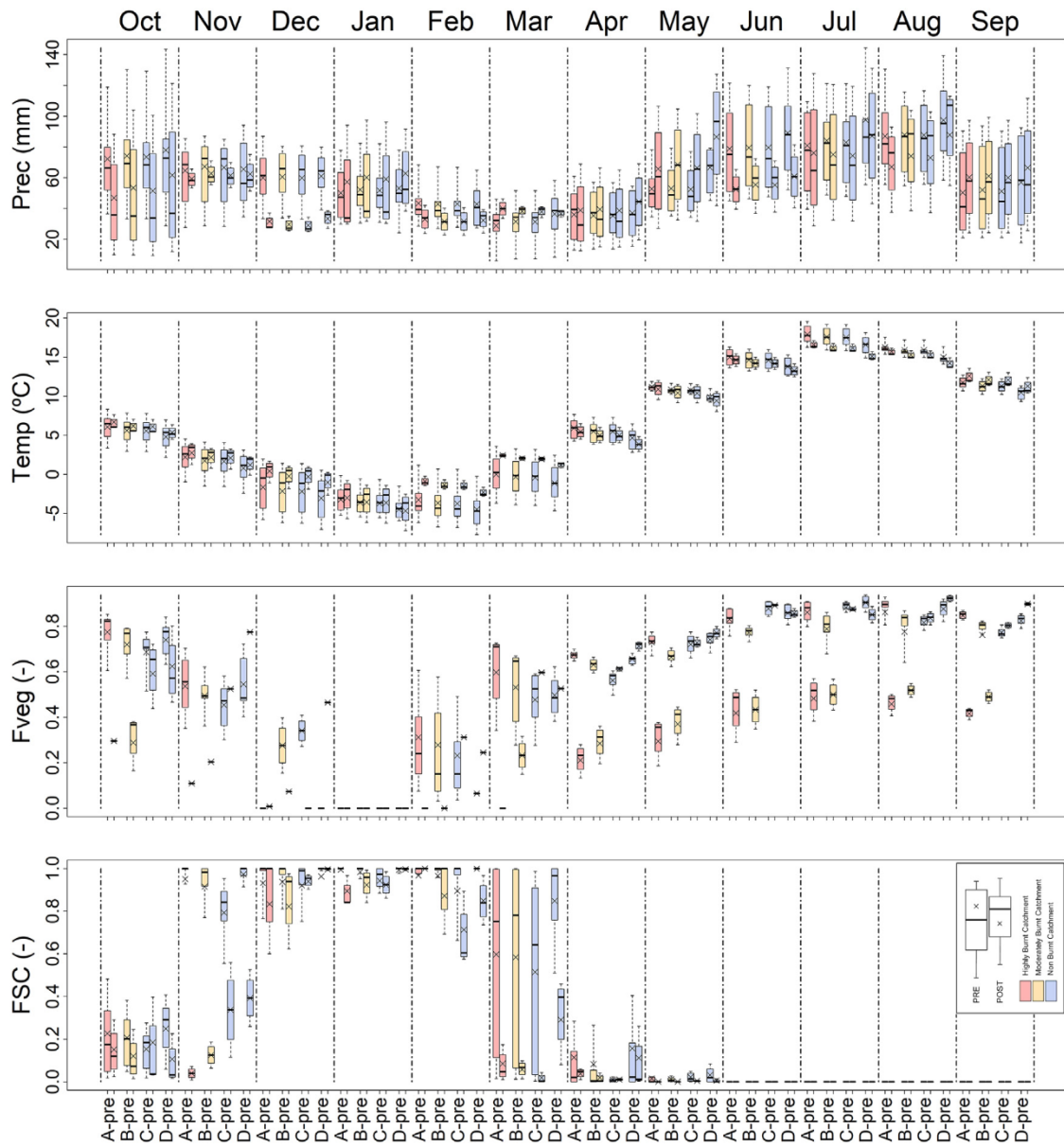


Fig. A3. Seasonal distribution of the climate and land cover descriptors defined at monthly scale for the pre- and post-wildfire period in each of the four selected sites. Red box highly burnt site; orange box moderately burnt site and blue boxes, non-burnt areas.

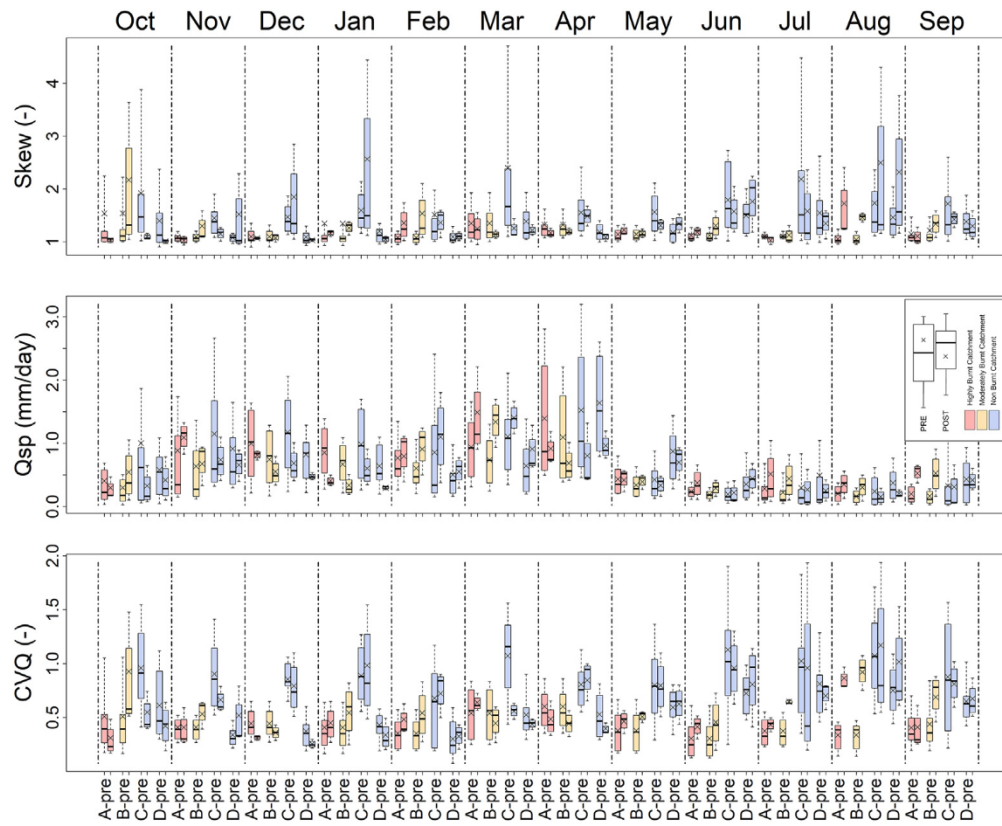


Fig. A4. Seasonal distribution of streamflow descriptors (flow signatures referring to magnitude) defined at monthly scale for the pre- and post-wildfire period in each of the four selected sites. Red box highly burnt site; orange box moderately burnt site and blue boxes, non-burnt areas.

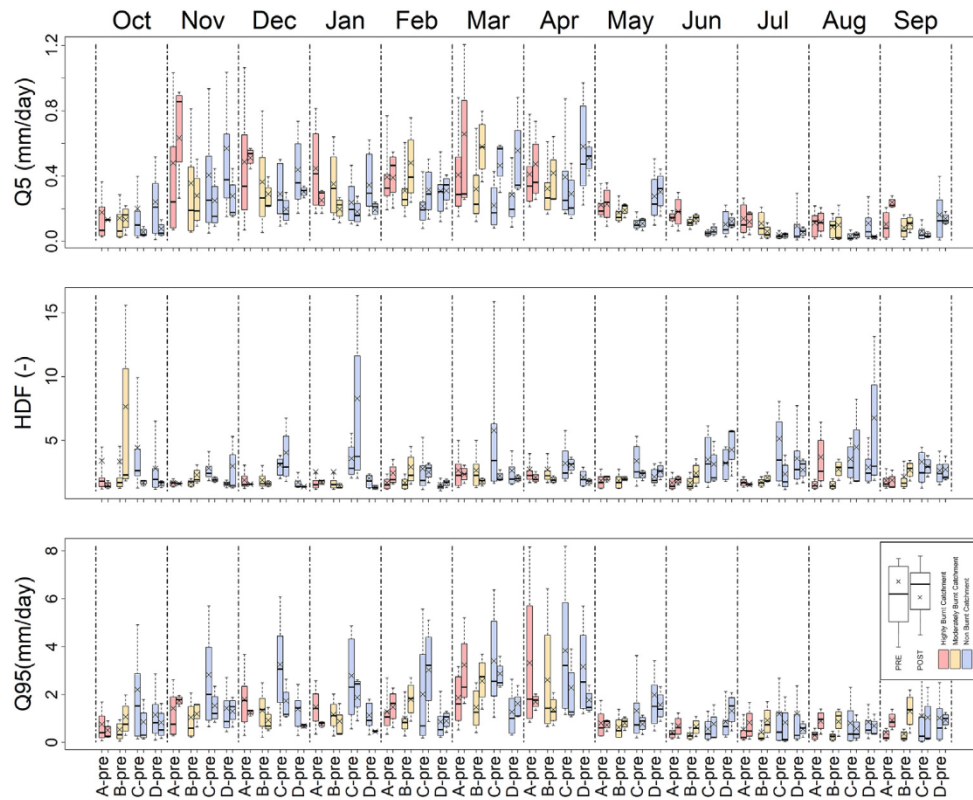


Fig. A5. Seasonal distribution of streamflow descriptors (flow signatures referring to duration and timing) defined at monthly scale for the pre- and post-wildfire period in each of the four selected sites. Red box highly burnt site; orange box moderately burnt site and blue boxes, non-burnt areas.

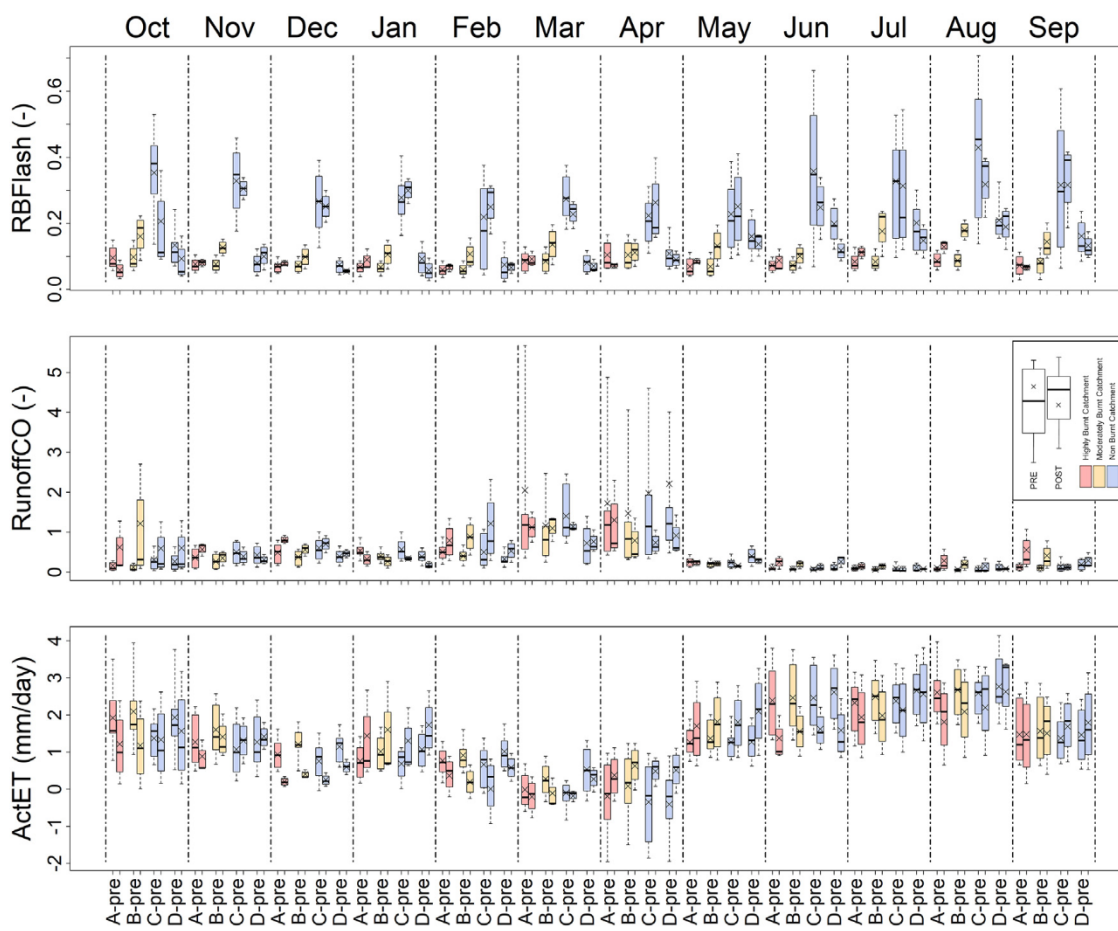


Fig. A6. Seasonal distribution of streamflow descriptors (flow signatures referring to catchment response) defined at monthly scale for the pre- and post-wildfire period in each of the four selected sites. Red box highly burnt site; orange box moderately burnt site and blue boxes, non-burnt areas.

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