ACTION GUIDE

Erosion hazard assessment after a fire

Experimental arrangement in the commune of Cerbère (Pyrénées-Orientales, France)

Interreg Sudoe MONTCLIMA
European Union
European Regional Development Fund

Contents

1. Purpose of this guide

1.1 The effect of climate change on the increase in fires

In recent years, *"regional increases in temperature, aridity and drought have increased the frequency and intensity of fires"*, with a spatial spread that goes far beyond the regions that were frequently affected previously. Over the next few decades, *"At a global warming of 2°C with associated changes in precipitation, global land area burned by wildfire is projected to increase by 35% (medium confidence)" (source: Intergovernmental Panel on Climate Change - Working Group II; contribution to the Sixth Assessment Report).*

By drying out the vegetation, climate change increases the meteorological hazard[1] of forest fires and lengthens the fire season. METEO FRANCE[2] researchers have studied the evolution of this hazard over the past century and for the next few decades: it has been increasing since the 1960s and is expected to increase further during the 21st century. Especially in the Mediterranean basin, all climate models predict a drying out. This area is thus defined as a climate change hotspot in the latest IPCC report.

[1] The **French Meteorological Fire Index (MFI)** is representative of the meteorological hazard associated with forest fires. The MFI is used to estimate the meteorological hazard of forest fire, taking into account the probability of its outbreak and its potential for spread. METEO FRANCE assesses the MFI daily throughout France. This index is calculated from simple meteorological data: temperature, air humidity, wind speed and precipitation. These data are fed into a numerical model that simulates the moisture conditions of the vegetation and the resulting **meteorological fire hazard**. Weather observations and forecasts are used to calculate a daily MFI. Climate projections allow us to study its evolution in the longer term.

[2] Extract from a METEO FRANCE publication: https://meteofrance.com/le-changement-climatique/observer-le-changement-climatique/changement-climatique-et-feux-de-forets.

The evolution and modelling of the MFI from 1958 to 2100 show a steady increase in the frequency of days with meteorological fire hazard and a lengthening of the fire season (starting earlier in spring and ending later in autumn). The territories exposed to this hazard are also expected to extend towards the north of France.

The mean value of the MFI increased by 18% between the period [1961-1980] and the period [1989-2008]. By 2040, the mean MFI is expected to be 30% higher than for the period [1961-2000]. Some simulations show that this increase could reach up to 75% by 2060. By this time, a year like 2003 would become the norm for meteorological forest fire hazard.

METEO FRANCE researchers have cross-referenced this evolution of the meteorological fire hazard with the maps of vulnerability to forest fires of the main forest stands, drawn up by the National Forestry Office (ONF) and the National Forest Inventory (IFN). Potential sensitivity maps for summer forest fires in the present [1989-2008] and medium terms [2031-2050] were drawn up.

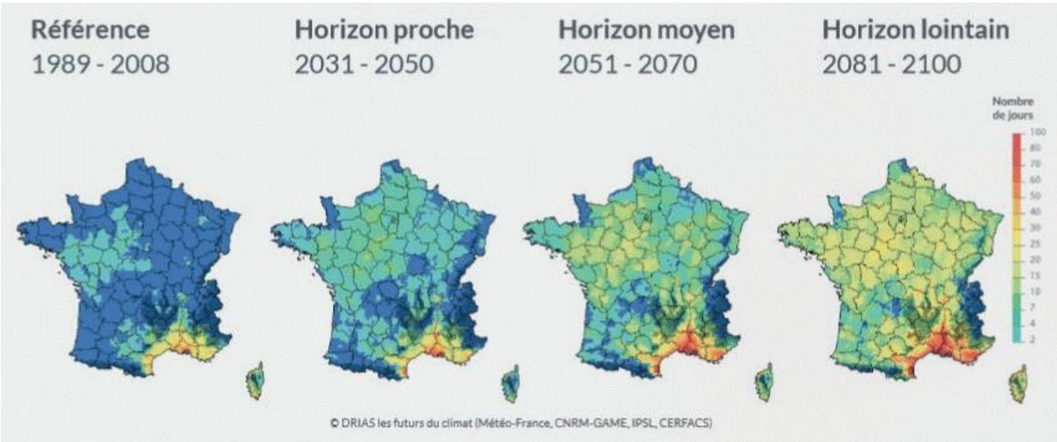


Figure 1: Number of days with meteorological fire index above 40 (high emission scenario)

1.2 Fires increase natural risks

After a vegetation fire, in mountainous terrain, the potential aggravations concern the following risks *(Extract from the DGPR document, ONF 2021: Synthesis of post-fire studies in methodological review):*

- **Risk of falling trees**
  Fire causes the death or weakening of trees, which greatly increases the risk of tree falls. This risk is created as soon as the wooded areas are reached by a fire of medium or high severity. In most cases, the trees fall months or possibly years after the fire has caused their death by heating the living parts (meristems), accentuated by degradation by various decomposing organisms (entomofauna and fungi in particular). In the case of trees that are already partially dead or desiccated, tree fall can occur during or immediately after the fire.

Falling trees can lead to the aggravation of other risks (erosion, rock falls, overflowing watercourses, avalanches).

- **Risk of falling rocks and stones**

  In the zones of origin, fire facilitates the movement of rocks through the combined effect of heat-induced soil destructuring and increased erosion due to the loss of vegetation cover.

  In rockfall propagation zones, the destruction or damage of the forest by fire can lead to a sudden loss of the protective screen function and therefore greatly increase the probability of danger to important structures.

  Protective structures can also be damaged, diminishing their effectiveness in reducing the probability of stones and rocks falling (active structures) or of their reaching other important elements (passive structures): wooden structures can be totally destroyed, dry stone walls destabilised, concrete or metal structures can be damaged by thermal effects, with the appearance of problems with anchoring and the resistance and durability of building materials.

- **Risk of gullying and erosion**

  During a fire, the heat destructures the surface soil and destroys the plant litter and the herbaceous layer, facilitating the genesis of erosion and gullying phenomena. Furthermore, the layer of ash deposited on the ground during the fire is highly mobile, and is easily washed away at the first rainfall. Erosion and gullying occur mainly in the first year after the fire and up to the third year. After this period, the most destructured fraction of the soil has already been washed away and the herbaceous and shrub layer is again present to protect the soil.

  These post-fire phenomena can then have two types of consequences:

  › **on natural hazards**: erosion and gullying lead to the bottom of thalwegs becoming filled with gravel and scouring of the slopes, as well as on the tracks. Indirectly, erosion favours the movement of stones and rocks, which will actually fall later when dislodged by overflowing mountain streams;

› **on the environment**: soils are not only an important reservoir of biodiversity and carbon, but also a substrate for the development of the whole local biosphere. Fires have a surprisingly strong impact on ecosystems (directly through flames, then indirectly through erosion). These impacts are all the more serious when fires are intense and/or frequent; in this case, the ecosystems are increasingly degraded (monospecific scrubland, grasslands, scree, deserts).

- **Risk of flooding and of overflowing watercourses**

  The destruction of the vegetation cover and the weakening of the soil by fire considerably aggravate the processes of runoff and gullying and therefore the risk of flooding and overflowing watercourses, including far downstream of the catchment areas affected by the fire. Post-fire damage usually occurs at already problematic locations (structures that cross the path of the water, bridges, culverts, restricted stretches of watercourses, flooding areas, etc.).

  An aggravating factor is the formation of logjams of burnt wood along the river system.

  The transport of solids is most significant during the first rainy episodes after the fire (departure of ash and the upper fraction of the soil disintegrated by the fire). It is therefore essential to assess this risk very quickly, before the autumn period of intense Mediterranean rainfall. This risk disappears as soon as a cover of at least 50% of the burnt surface is reconstituted, either artificially (mulching) or more often naturally (herbaceous plants, shoots or seedlings of shrub or tree species, etc.).

- **Avalanche risk**

  In potential avalanche departure zones, the destruction of protective forest stands by fire can considerably increase the avalanche risk (more frequent avalanches with large volumes). Fire can also damage and weaken avalanche defence structures of any material (metal, reinforced concrete, wood, stone).

1.3 The state of current knowledge and limitations on runoff and erosion

For this case study, we are **only** interested in **the phenomena of runoff and soil erosion** after a fire.

1.3.1 Changes in hydrological regime

A wildfire very often changes the hydrological regime of a catchment area because it changes the input parameters:

- The strong decrease of the **interception** effect of crown cover due to its disappearance (and of vegetation more generally) generates greater **effective rainfall** than when vegetation is fully present;
- The **runoff coefficient** is increased because the land use is strongly modified: the disappearance of low vegetation no longer allows for the slowing of runoff, which preferentially runs down any slope rather than partially infiltrating the soil;
- Potential **hydrophobicity of** the soil[3] (a **crust** of cinders generated by the percolation of organic waxes from the burning of plants) which strongly reduces the infiltration capacity of the soil;
- The **"splash effect"** of raindrops that strongly impact the soil, aggravated by the lack of any interception. This splash effect contributes to the formation of a crust, which considerably reduces the infiltration potential of the soil: whereas in a non-porous and loose soil, infiltration is of the order of 30-60 mm/h, with a crust this infiltration is heavily reduced and reaches values of the order of 2-6 mm/h, i.e. 10 times less;
- **The washing away of the humus layer** in the case of a litter fire, which reduces the retention capacity of rainfall, and thus aggravates runoff (*Combes, 1990*);
- Decreased runoff **concentration time** due to increased runoff velocities on bare soil.

Many publications deal with changes in the hydrological regime after a fire. Several configurations (soil type, slopes, vegetation) were analysed, and it was found that in the majority of cases post-flood flows are significantly increased.

[3] The phenomenon of hydrophobicity is very often mentioned in English-language studies on large coniferous fires and on homogeneous soils with a significant silty fraction. In a Mediterranean context, on rather coarse and gravelly soils, this hydrophobicity phenomenon seems less prevalent. A DGPR 2022-2023 action sheet is being drafted to assess the relevance of taking this phenomenon into account.

This increase is in a wide range between +30% and +800% (*Lavabre 1992, 1996, 1997; Shakesby 2006*).

This range is based on a compilation of post-fire analyses from different countries (USA, Australia, Spain, Portugal, France) and a multitude of configurations. It does not specifically consider the impact of fires in the Mediterranean context.

The objective of this case study was therefore to specify, through measurement, the increase in hydrological regime on land frequently encountered in the PYRENEES-ORIENTALES *département* and subject to a strong forest fire hazard.

1.3.2 Erosion and gullying

Fire, depending on its intensity, will change the properties of the soil in several ways:

1. **The formation of a carpet of ash covering the ground.** Depending on the intensity of the fire, the ash produced can be either black to a thickness of often less than 1 cm (coals formed during a low-intensity fire) or grey-white to a thickness of up to 20 cm (fine, light ash from a high-intensity fire). Ash changes the porosity of the underlying soil in different ways: black, rather coarse ash remains porous and does not form a screen over the ground. In contrast, the very fine grey ash clogs the soil interstices more quickly and effectively (*Woods, 2008*).

2. **Modification of the impermeability of the upper soil stratum** (generally to a depth of less than 6 cm) through the formation of a hydrophobic layer (*MacDonald, 2009*). The hydrophobic nature of the soil caused by fire is often the main cause of increased runoff. Fire temperature is a critical factor in increasing the hydrophobic nature of post-fire soil (*Doerr, 2006*). In the case of deep, coarse-textured soil covered by scrub[4] and/or coniferous vegetation, the impact of the fire (for a duration of between 5 and 20 minutes) is as follows:

   - If the soil temperature remains below 175°C, the fire does not change the composition of the soil much and it does not become more hydrophobic than before;
   - If the soil temperature reaches values between 175°C and 200°C, the organic matter turns into wax, which clogs up the interstices of the soil, considerably increasing the hydrophobic nature of the soil. The rate of runoff then increases sharply;
   - If the temperature reaches 280°C - 300°C or more, the top layer of soil disintegrates and the hydrophobic layer is formed underneath.

[4] DOERR's study of 2006 concerns "chapparal"-type soils, a sort of maquis or bushy scrubland found in California, northern Mexico, and around the Mediterranean rim. This ecosystem belongs to the category of forests, wooded areas and Mediterranean maquis.

3. Alteration of the surface soil structure. In comparison, fire acts 10 to 100 times more intensely than frost in the long term to fracture rocks (*Shakesby, 2006*). Burnt soils become friable and much less cohesive, which generates a large quantity of fine materials (*COMBES, 1990*) that can be washed away by medium and heavy rainfall. The most intense fires can destroy at least 80% of the surface layer and litter *(MacDonald, 2009*).

The degree of soil erosion depends on many factors, including:

- The **level of soil destructuring** induced by the heat of the fire (this destructuring being itself strongly linked to the geology, the vegetation cover, the relief, the previous hydric conditions, etc.);
- **The aggressiveness of the rains:** splash effect[5], cumulative rainfall and hourly intensities.

Given the many factors that control the degree of soil erosion, it is very difficult to estimate sediment production immediately after a fire.

Several publications (*Ballais, 1992; Martin, 1993; Lavabre, 1997; Shakesby, 1996*) have analysed sediment production after a fire. The values vary greatly depending on the configuration of the sites (geology, type of vegetation, rainfall context).

Some publications mention an increase in water erosion by a ratio of 1 to 650 between the pre-fire and post-fire situation, with a return to normal between 1 year (low rainfall) and 5 years (high rainfall). Other publications, in different contexts, suggest an increase in water erosion by a ratio of 1 to 6000, with sediment production rates highest in the year following the fire and decreasing up to 3 to 5 years after the fire.

The goal of this case study was therefore to specify, through measurements on erosion plots, the increase in water erosion on land frequently encountered in the PYRENEES-ORIENTALES *département* and subject to a strong forest fire hazard.

[5] Following a fire, the absence of crown cover considerably reduces the interception of rain by trees. The direct impact of raindrops on the soil contributes to a significant splash effect on the soil, which is all the greater when the rain comes from a thunderstorm (Pietraszek, 2006) because the drops have a larger diameter (summer thunderstorms, Mediterranean-type rain).
Raindrops falling on the ground produce a splash effect that can dislodge soil material.
To give an order of magnitude of the aggressiveness of the splash effect, a rainfall equivalent to a 1 mm water drop falling at a distance of 10 cm from the ground can loosen up to 10 grams of material per m2 of soil, i.e. about 100 kilograms of soil per hectare. The splash effect is one of the main processes of hydraulic soil erosion. Even in the absence of runoff, it is likely to cause the creep of sedimentary particles.

2. The proposed methodology

2.1 The goals

An overview of the literature gives very wide ranges with regard to increased hydrological and erosion.

The objective of this study was to quantify very precisely the impact of a fire on the modifications of the hydro-sedimentary regime, in a configuration frequently encountered in the PYRENEES-ORIENTALES *département*: wooded maquis on predominantly schistose soil.

2.2 The experimental approach

Post-fire erosive processes were quantified precisely by setting up experimental plots for hydro-sedimentary measurements.

2.2.1 Principle of measuring instrumentation

In order to have a precise knowledge of the liquid (hydrology) and solid (water erosion) flows, according to the type of land (burnt, not burnt), the choice of instruments was designed to measure two categories of values, as illustrated in the following diagram:

- **Continuous measurements:**
  - runoff
  - low time-step rainfall
- **Final measurements:**
  - mass of eroded sediment

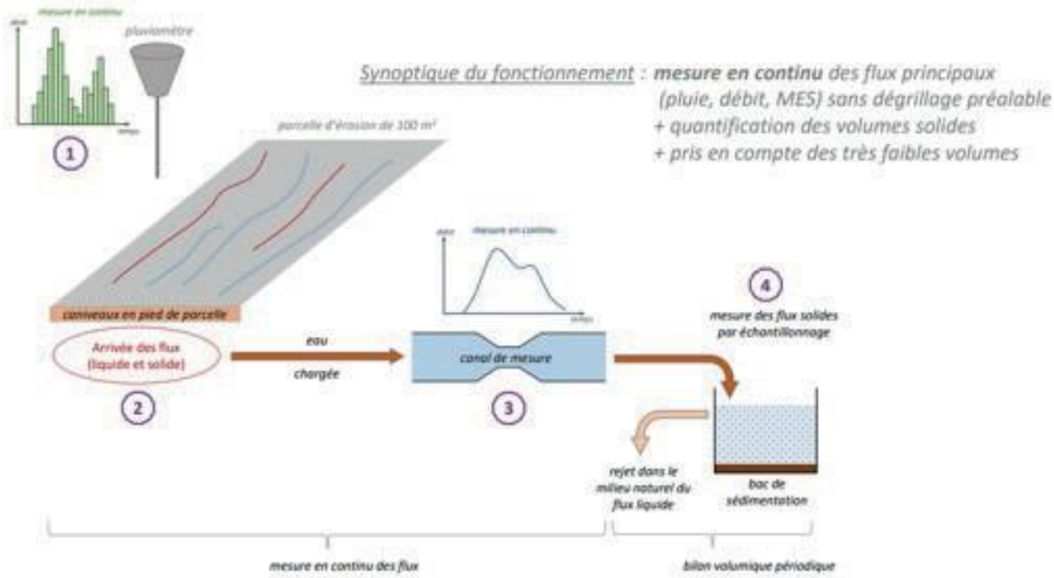


Figure 2: Schematic diagram of the operation of an experimental erosion plot

In order to easily demonstrate the impact of a fire on the increase in runoff and erosion, three experimental plots were established:

- 1 plot of shrubby maquis that had been burnt over **(Fire Plot 1)**
- 1 plot of dense shrubby maquis that had been burnt over **(Fire Plot 2)**
- 1 plot of dense shrubby maquis, not burnt **(Control Plot)**

Each of the plots had an area of about 100 m^2 (5 metres wide and 20 metres long down the slope). The plots were marked out with boundary markers laid and packed on the bare ground (and not driven into the ground) in order to avoid as much as possible disturbing the soil and thus the actual erosion measurement.

The gauge channel used was the 0.8-foot Hs-Flume model. This type of equipment can measure flows over a wide range [0.0085 l/s - 12.94 l/s] and is not very sensitive to silting of the channel bottom.

2.2.2 Site selection

All the equipment was designed and sized during the summer of 2021, in anticipation of a fire that might occur. This "opportunistic" strategy required the pre-identification of interesting sites to be equipped with measuring instruments.

The pre-identified sites, according to their geological, rainfall and relief characteristics and their susceptibility to fire were, in order of priority:

- La Côte Vermeille
- Les Albères
- Les Fenouillèdes
- Le Bas Vallespir
- Les Aspres
- Aude *département* - Corbières Alaric

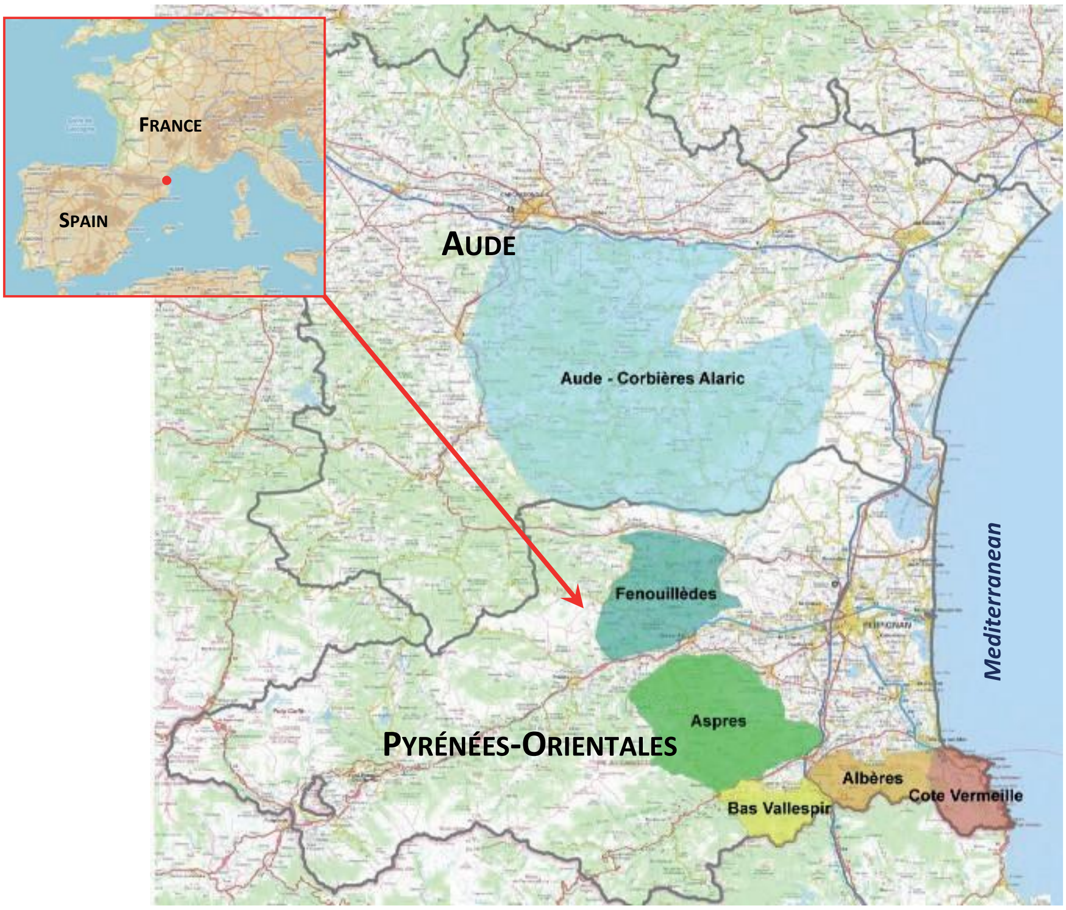


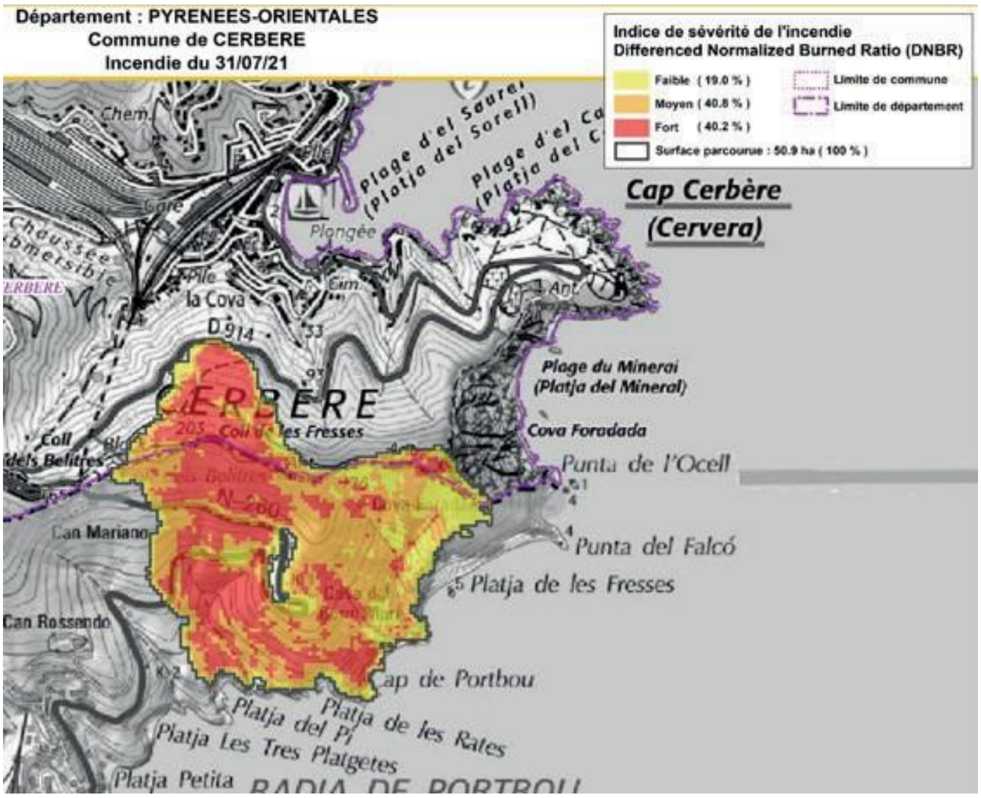
Figure 3: Location of possible sites to be equipped with measuring instruments because of the potential for fires

On 31 July 2021, a fire broke out in the Commune of Cerbère, and spread, driven by a strong tramontana wind, over 51 ha as far as PORTBOU (10 ha on the French side and 41 ha on the Spanish side).

The burnt vegetation was mainly composed of heath and scrub (50 ha) and marginally of closed coniferous forest (1 ha).

On the French side, all the burnt vegetation was in the Cerbère state forest (under forestry management). The severity index on vegetation was mostly High.

Figure 4: The fire started at about 5 p.m. on 31/07/2021 (top left, view from the heights of CERBERE, Chemin des Vignes). Development of the fire (top right) and its ultimate burnt area straddling the French-Spanish border (bottom right).


Département : PYRENEES-ORIENTALES
Commune de CERBERE
Incendie du 31/07/21
Indice de sévérité de l'incendie
Differenced Normalized Burned Ratio (DNBR)
Faible (19.0 %)
Moyen (40.8 %)
Fort (40.2 %)
Surface parcourue : 50.9 ha (100 %)
Limite de commune
Limite de département
Cap Cerbère
(Cervera)
Plage du Minerai
(Platja del Mineral)
Cova Foradada
Punta de l'Ocell
Punta del Falcó
Platja de les Fresses
Cap de Portbou
Platja de les Rates
Platja del Pi
Platja Les Tres Platgetes
Platja Petita
CERBERE
Coll des Fresses
Can Mariano
Can Rossendo
la Cova
D914
N-260
Plongée

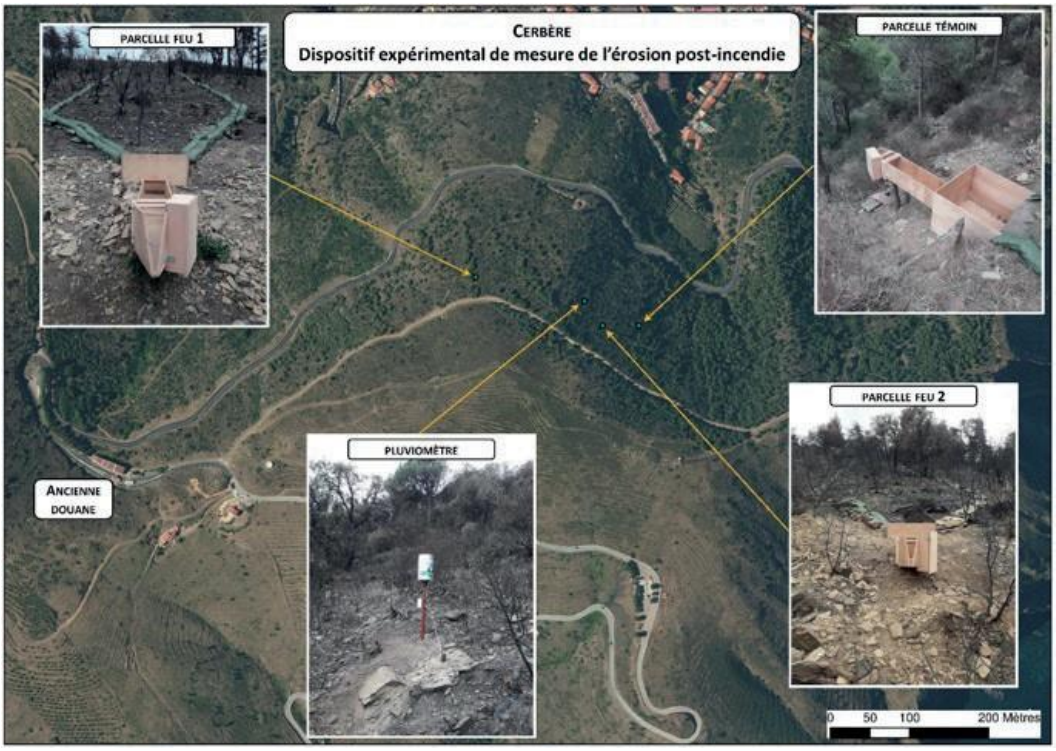
2.2.3 Setting up the measuring instruments

The equipment was installed during September and October 2021. The installations were operational on 21 October 2021, less than 3 months after the fire (31 July 2021).

During these 3 months, there was no significant rainfall event that could begin to leach the soil.

The installation consisted of:

- 3 erosion measurement plots
  - 1 plot covered by fire → Fire Plot 1
  - 1 plot covered by fire (steeper and with more vegetation) → Fire Plot 2
  - 1 plot not affected by fire → Control Plot
- 1 automatic rain gauge (located in the centre of the 3 plots)



The characteristics of the plots were as follows:

	Area	Longitudinal slope	Distance to rain gauge	Type of vegetation
Fire Plot 1	115 m²	44%	130 m	Shrubby scrub
Fire Plot 2	107 m²	53%	40 m	Dense shrubby scrub
Control Plot	114 m²	56%	70 m	Dense shrubby scrub

The three erosion plots were identical, and consisted of:

- a **plot of land** with an area of approximately 100 m² delimited by **boundary markers** laid and packed into the natural ground (this choice of marker was needed because the ground is very stony and thin curbs cannot be easily inserted). The boundary markers at the bottom of the plot converged to channel the water to the measuring device;
- a wooden **sedimentation tank** with a side length of 80 cm which receives the run-off. Coarse material (sand and stones) and plant debris settle in this tank;
- a 1.2 m long **approach channel** to channel the flows,
- a 0.8 foot **Hs-Flumes flowmeter** with its remote measuring well. The measuring well is fitted with a **water level logger** (Level TROLL 500 from InSitu). The specific shape of the flow meter reveals the flow rate based on the measured water level;
- an **automatic camera** (time lapse and motion detection) to record the flows coming out of the flow meter.

3. Results

3.1 Increased hydrological regime

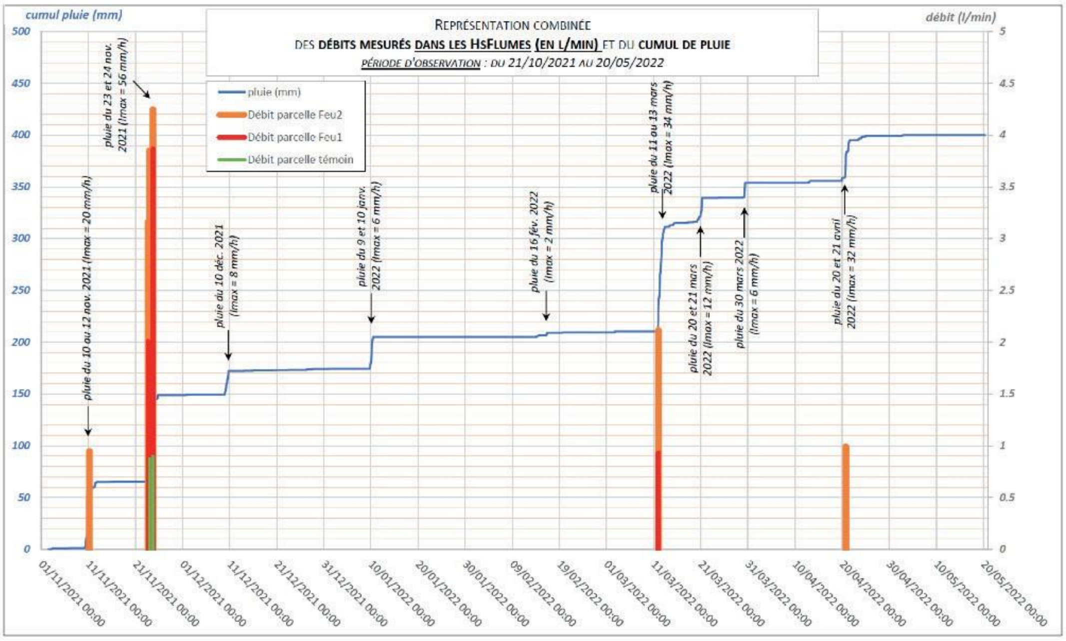
The experiment was launched in the autumn of 2021 and is still in operation today. The results presented below are for the period from 21/10/2021 to 20/05/2022, i.e. for 7 months. Only one hydrological season (autumn 2021 - spring 2022) was studied. The results are therefore not very robust, but they do allow trends to be identified.

The graph below illustrates the hydrological responses over one hydrological season.

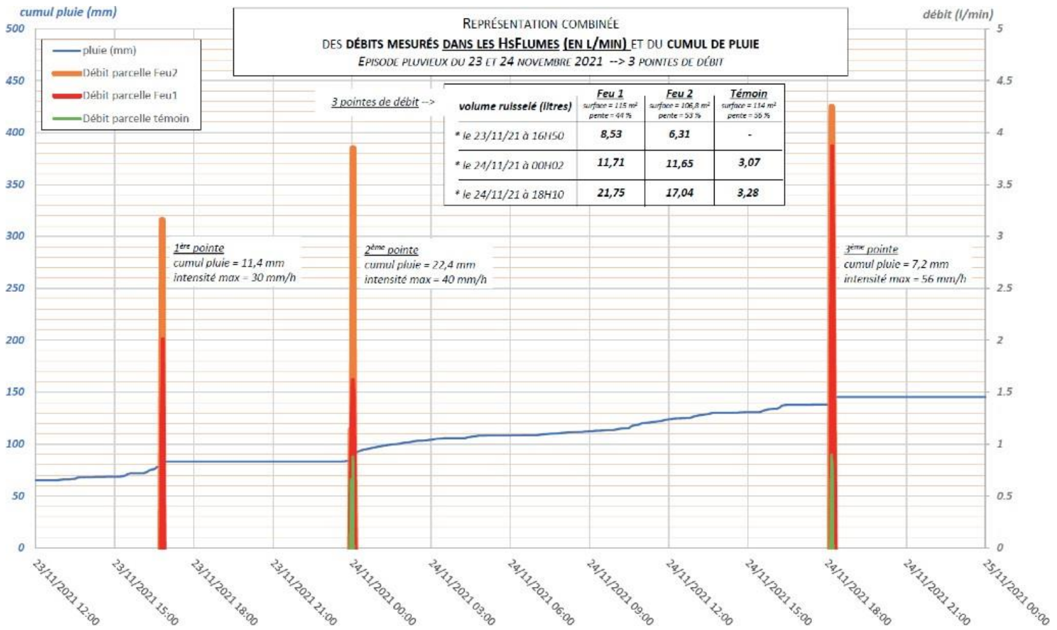
It can be seen that Fire Plot 2 (the steepest burnt plot) reacted very quickly and most strongly. Fire Plot 1 (less steeply sloping burnt plot) reacted less quickly and more moderately than Fire Plot 2. The Control Plot reacted little.

The hydrological response was very much related to the value of the rainfall intensity, not to the total rainfall accumulation over the episode.

The first hydrological responses (Fire2) occurred from a rainfall intensity of 20 mm/h.



The detailed analysis of the rainy episode of 23 and 24 November 2021 provides a better understanding of the rainfall thresholds that triggered the hydrological responses of the plots.



Rain on 24/11 at 0002 hours	Max. measured flow rate (l/min)	Multiplier coeff.	Runoff volume (litres)	Multiplier coeff.
Plot with vegetation (control) slope = 56%	0.66	*reference*	3.07	*reference*
Fire Plot 1 slope = 44%	1.62	*x 2.5*	11.71	*x 3.8*
Fire plot 2 slope = 53%	3.85	*x 5.8*	11.65	*x 3.8*

Rain on 24/11 at 1810 hours	Max. measured flow rate (l/min)	Multiplier coeff.	Runoff volume (litres)	Multiplier coeff.
plot with vegetation (control) slope = 56%	0.90	*reference*	3.28	*reference*
Fire plot 1 slope = 44%	1.42	*x 1.6*	21.75	*x 6.6*
Fire Plot 2 slope = 53%	4.24	*x 4.7*	17.04	*x 5.2*

With regard to the hydrological results, it can be seen that the burnt plots produced more runoff volume with a higher flow rate than the plot with vegetation used as a reference.

The flow values were 1.6 to 5.8 times higher than the flow measured on the reference plot.

As far as runoff volume is concerned, the values were 3.8 to 6.6 times higher than the volume produced by the reference plot.

Furthermore, this experiment showed that runoff was much more sensitive to the intensity of rainfall than to its total volume.

Runoff from the **plot with vegetation** started when rainfall intensities exceeded **40 mm/h**.

In contrast, runoff from the **burnt plots** started as soon as the rainfall intensity exceeded the threshold of 20 mm/h.

We therefore conclude that in a context of Mediterranean vegetation of the shrubby maquis type on schistose soils, and for light and moderate rainfall, only half the rainfall intensity is required to generate runoff on burnt soil than on non-burnt soil.

3.2 Increased erosion

The erosion products are periodically taken from the sedimentation tanks to be weighed. During the measurement period, sediments were collected twice: on 17 November 2021 and on 7 January 2022. During the other visits, the quantity deposited was not sufficient to be measured.

The equivalent erosion rates were very variable, between the Control Plot with vegetation (7 Kg/ha), Fire Plot 1 (53 Kg/ha) and Fire Plot 2 (80 Kg/ha).

On the Control Plot, the majority of the material was plant debris and very fine sand. On Fire Plot 1, the deposits were composed of sand and pebbles, while on Fire Plot 2 the deposits were mainly pebbles.

	date de relevés des sédiments		*sur la période 21/10/2021 --> 20/05/2022*	
	17/11/2021 masse en grammes	**07/01/2022** masse en grammes	Cumul (Kg) sur la parcelle	***érosion équivalente t/ha***
parcelle Feu 1	**170**	**440**	0.61	***0.053***
type de dépôts	*nombreux sables et cailloux* *beaucoup de suie et débris de végétaux*	*nombreux sables et cailloux* *beaucoup de suie et débris de végétaux*		
parcelle Feu 2	**315**	**540**	0.855	***0.080***
type de dépôts	*nombreux sables et cailloux* *beaucoup de suie et débris devégétaux*	*nombreux sables, forte proportion de cailloux* *beaucoup de suie et débris de végétaux*		
parcelle Témoin	pas de sédiments	**75**	0.075	***0.007***
type de dépôts	-	*sables très fins et suie* *beaucoup de débris de végétaux*		

Taking the erosion rate as a reference, the erosive potential was 8.1 times higher on Fire Plot 1 and 11.4 times higher on Fire Plot 2.

Sediment results over the period from 21/10/2021 to 20/05/2022	**Mass of sediment measured (kg)**	**Equivalent erosion (t/ha)**	**Multiplier coeff.**
Slope of plot with vegetation = 56%	0.075	0.007	*reference*
Fire Plot 1 slope = 44%	0.61	0.053	*x 8.1*
Fire Plot 2 slope = 53%	0.855	0.080	*x 11.4*

3.3 Limitations on the use of the results

The results of the analysis may appear to be accurate, but they should be taken with some caution, particularly as:

- the very small size of the plots means that we were obliged to consider unaveraged quantities, unlike in a larger catchment area, which gives quantities that are within the strong margin of the real quantity;
- the short duration of the measurement period does not allow for averaging the values over time. It would only require too little or too much rainfall over the observation period to distort the likely values that could be obtained over a longer observation period;
- there are uncertainties about the proportion of natural erosion to be measured as opposed to anthropogenic erosion generated during the installation of equipment;
- there are uncertainties about the effectiveness of plot containment using border markers,
- there are approximations regarding the setting to zero of the water level probes.

Rather than using the absolute values of the quantities, we advise considering the trends that are displayed and the relative comparison between plots.

4. Lessons learnt from the project

The quality of the results depends on the following parameters:

- Location and configuration suitable for the measurements sought;
- Quality of equipment installation;
- Choice of equipment, including accuracy and reliability;
- The ability to travel frequently to the site to supervise the device;
- The possibility of working on long time periods, i.e. over at least 2 hydrological years;
- The occurrence of a exceptional rainfall immediately after the fire.

This experiment shows that on schistose soils, with shrubby scrub vegetation and on slopes of around 40%-50%, fire has a real impact on increasing hydro-sedimentary processes:

- Soils become more reactive to precipitation
- Runoff volumes and flows are increased, by remarkable ratios of 1 to 6
- Water erosion is strongly increased, by ratios of 1 to 11, with intense erosive processes during the first year after the fire.

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