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# Sediment and organic carbon discharges to the coastal oceans by badlands (English Channel, Normandy, France)

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## Abstract

Determining sedimentary and organic carbon fluxes and sources within the sedimentary continuum from land to sea is crucial for improving the understanding of Earth system dynamics, global carbon budgets and associated biogeochemical cycles, especially in the context of Global Change. Among continental sources, marly badlands, characterized by high erosion rates and significant Total Organic Carbon (TOC) contents, are potential contributors of material to the sea. However, data on sediment and TOC yields, fluxes and the contribution of badlands to the marine environment are still limited, particularly in NW Europe and oceanic regions. In this context, the instrumented sites of Vaches Noires cliffs on the western Normandy coast, France, were studied over three years. Suspended Particulate Matter (SPM) and source samples were collected along the eastern part of the cliff. Geochemical analyses, sediment fluxes and yields were obtained and compared with those from local rivers, European badlands and worldwide Small Mountain River systems (SMRs). These first results show that the cliffs exhibited high productivity in terms of sediment and organic carbon (OC) yields, like other studied badlands. Reaching the English Channel, material from badlands can enter and sediment within the Seine estuary, contributing to the Turbidity Maximal Zone and mixing with other OC sources (such as primary productivity and continental OC). Although the contribution of this material to the carbon (C) budget of this interface remains uncertain, it could be significant, especially with the increase in global sea level and major rainfall events.

## KEYWORDS

badlands, rock-Eval 6 pyrolysis, suspended sediments (SPM), Vaches Noires, yields

## 1 | INTRODUCTION

The characterization of material and nutrient fluxes between Earth's reservoirs (ocean, atmosphere, land, soil, biomass and lithosphere) is essential for a comprehensive understanding of Earth system dynamics, particularly the global carbon cycle. Among these fluxes, the lateral transport of Suspended Particulate Matter (SPM) from land to sea by rivers plays a crucial role in regulating ocean chemistry and contributing to the global chemical equilibrium of Earth's reservoirs (e.g., Jeandel & Oelkers, 2015). The exchanges between continental surfaces and the ocean are also key components of the carbon cycle (Bauer et al., 2013; Bauer & Druffel, 1998; Ciais et al., 2008). These

exchanges redistribute substantial amounts of terrestrial carbon to the coastal ocean (0.95 Pg/y) through processes such as leaching and erosion. This redistribution mitigates the efficiency of the terrestrial carbon sink (i.e., biomass and soils, Regnier et al., 2013).

Among the sources of sediments delivered to the global ocean, it is well established that rivers are the dominant drivers, contributing approximately 18 Pg/y (Milliman & Farnsworth, 2013). This riverine flux is 10 times greater than that from glacial input (1.4 Pg/y, Raiswell et al., 2006) and 40 times greater than eolian transport. To develop a comprehensive framework for sediment transport from continental surfaces to the ocean, it is also necessary to account for the erosion of rock coasts. Recent updates indicate that rock coast erosion

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contributes an additional 0.6 to 2.4 Pg/y, or about 10% of the sediment supplied by global river systems (Milliman & Farnsworth, 2013; Regard et al., 2022).

A focus on Europe reveals that the contribution from coastal erosion (46 to 176 Tg/y) constitutes 16 to 61% of European river discharges (290 Tg/y), underscoring a significant input of sediments from rock coasts to the oceans (Regard et al., 2022). Regarding particulate organic carbon (POC) associated with SPM, the global flux to the oceans from rivers is well documented, estimated at approximately 0.15 to 0.20 Pg C/y (Galy, Peucker-Ehrenbrink, & Eglinton, 2015; Hedges, Keil, & Benner, 1997; Ludwig, Probst, & Kempe, 1996). However, the contribution of POC from coastal erosion remains unknown.

Focusing on river systems, the origin of these materials is not spatially and homogeneously distributed across continental surfaces. Certain hot-spots, known for their high erodibility, are well documented. These can be summarized into two types: (i) Small Mountain Rivers (SMRs) which exhibit high erosion rates and deliver significant sediment loads to the global ocean (Milliman & Syvitski, 1992), and (ii) badlands, characterized by poorly consolidated rocks (e.g., shales, marls), a dense network of gullies and severe erosion rates (Gallart et al., 2013; Nadal-Romero et al., 2021), capable of delivering substantial amounts of sediments and associated fossil organic carbon. For instance, the badlands in the Rhône catchment cover only 0.2% of its total area but contribute 14% of the suspended sediments annually transported to the Mediterranean Sea (Copard et al., 2018). If such continental hot-spots exist, it is logical to assume the presence of coastal hot-spots as well. Similar to continental areas, the spatial distribution of coastal erosion rates is heterogeneous and typically influenced by climatic (temperature, precipitation), geological (lithology) and anthropogenic (coastal management) factors. Accordingly, for rock coasts, it is reasonable to consider that the occurrence of badlands, composed of soft rocks, could also represent hot-spots of coastal erosion. Badlands are developed in various regions under different climatic conditions. Although their spatial and temporal evolution can differ, they tend to converge towards similar forms (Bryan & Yair, 1982; Howard, 1994; Kasanin-Grubin & Bryan, 2007). When these badlands contain marly or shaly components, they are enriched in fossil POC. Having a fossil origin, this carbon has already completed a cycle in the sedimentary process and, having escaped diagenetic processes before its exhumation, it is more resistant to surface weathering processes compared to carbon recently produced by photosynthesis (Blattmann, 2022; Copard, Amiotte-Suchet, & Di-Giovanni, 2007). Consequently, this fossil POC can contribute significantly (up to 25%) to the lateral transport of carbon to coastal oceans (Galy, Peucker-Ehrenbrink, & Eglinton, 2015).

Once sediments, varying in organic carbon (OC) content, reach the land-sea boundary, they mix with marine OC and are primarily trapped within coastal, deltaic and estuarine environments (Bianchi & Allison, 2009; Burdige, 2007). The POC derived from riverine and coastal erosion sources exhibits diverse origins (detailed for riverine POC in Copard et al., 2022) and can be broadly divided into two main components: the first consists of more recent POC produced by modern photosynthesis (biospheric POC), and the second originates from the fossil (long-term) carbon cycle (fossil POC) released after the erosion of sedimentary rocks. Ultimately, the latter component, being more recalcitrant than its biospheric counterpart—both terrestrial and marine—can escape processes such as oxidation and biodegradation,

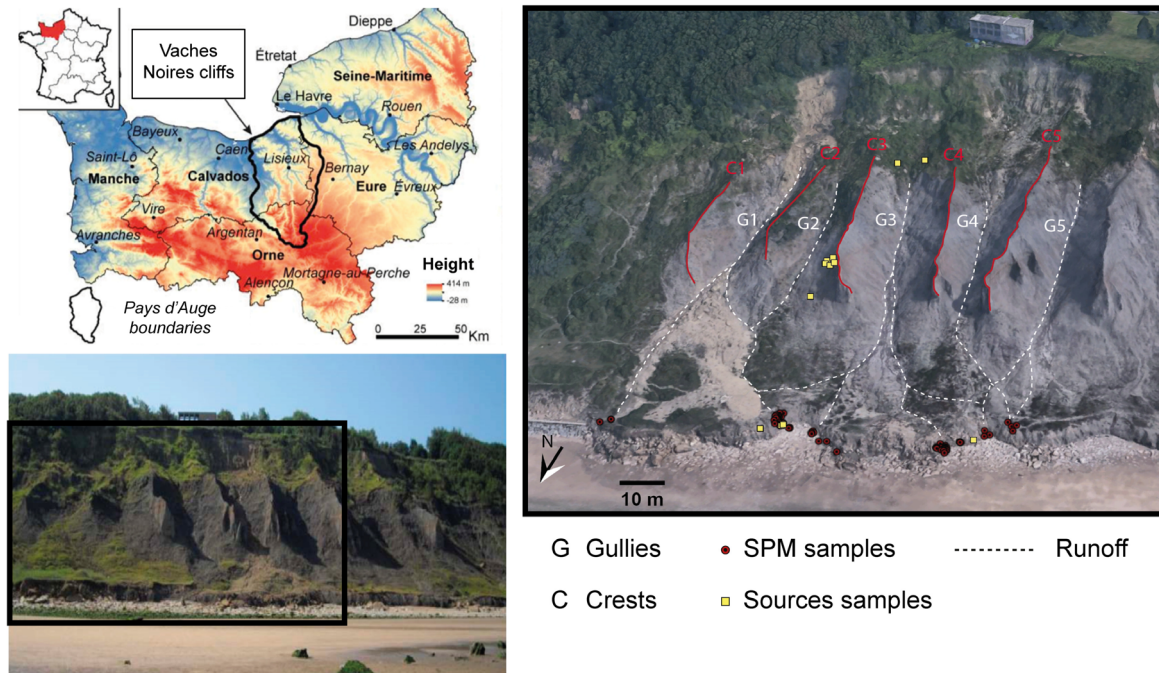
be preserved in marine sediments and serve as a valuable source tracker.

This work focuses on coastal badlands, considered an original coastal hotspot of erosion. While numerous studies have investigated these formations in the continental domain (see review in Gallart et al., 2013), there has been a lack of studies examining particulate fluxes (SPM and POC) from coastal badlands. In this context, the exported materials will directly supply the coastlines and estuaries with fast and short transport to the sea. This study aims to investigate SPM fluxes along a French land-sea continuum situated in the Seine Bay, where previous studies primarily considered only river inputs (Dubrulle et al., 2007; Lesourd, 2000). Several objectives motivated this work: (i) determining SPM fluxes from different gullies in the marly cliffs and identifying their sources, (ii) evaluating POC fluxes and the overall yield of coastal marly badlands and (iii) estimating the contribution of these coastal badlands to the organic carbon flux in the Seine estuary and comparing the POC contribution from this environment on a larger scale.

## 2 | STUDY SITE

The study site is located in the northwestern part of Normandy (France), within the Seine estuary, covering an area of 5,000 km<sup>2</sup>, and is widely open to the English Channel (Figure 1). On the eastern side, the Seine River supplies sediments and water to the English Channel by draining a watershed of 79,000 km<sup>2</sup>. The Seine is the major river flowing into the English Channel, with a mean annual discharge of approximately 400 m<sup>3</sup>/s, and extreme values ranging from 200 to 2000 m<sup>3</sup>/s. The mean annual mass of suspended particulate matter in the river discharge is estimated to be around  $6.0 \times 10^5$  t/y (Table 1). In the southern area, the cliffs of Vaches Noires, extending for nearly 4.5 km, are dissected by 87 major gullies that convey sediments to the English Channel. These cliffs are subjected to the combined action of subaerial and marine processes, including landslides, mudflows and sea erosion.

Samples from the marly limestone Jurassic badlands area were collected from this instrumented catchment, located between Houlgate and Villers-sur-Mer. Due to their specific sedimentary dynamics (mass movements), the cliffs, which are part of the French national observation service DYNALIT (Dynamique du Littoral et Trait de Côte) belonging to the INSU (Institut National des Sciences de l'Univers – National Institute of Sciences of the Universe), are subject to specific instrumentation (Roulland et al., 2022). The “Pays d’Auge” plateau is a relatively flat surface, interrupted by a few deeply incised and drained valleys. It terminates abruptly at the cliffs of the Vaches Noires, which contact the epicontinental sea of the English Channel. The main escarpment reaches an altitude of 112 m near Houlgate (west side) and narrows towards Villers-sur-Mer (east side), with a minimum altitude of 43 m and an average altitude of 66 m (Table 2). Perched valleys drained by intermittent streams running south-southeast to north-northwest, incise the plateau in the northern part over widths ranging from 40 to 130 meters. The elevation of the secondary escarpment where the active gullies are located does not vary significantly, ranging from 70 m in the western part to 55 m in the eastern part (Figure 2). Incision depths vary from 8 to 37 m (Roulland et al., 2019).



**FIGURE 1** The “Vaches Noires” cliffs in Normandy, France, showing the locations of gullies, suspended particulate matter (SPM) sampling sites and sources within the study area.

**TABLE 1** A literature review of the sediment flux of the Seine River.

Sediment flux (t/y)	References
$6.0 \times 10^5$ to $7.0 \times 10^5$	Lesourd, 2000
Mean: $6.0 \times 10^5$	Dubrulle et al., 2007
Extreme values: $1.3 \times 10^5$ – $1.7 \times 10^6$	
$4.9 \times 10^5 \pm 2.9 \times 10^5$	Landemaine & Cerdan, 2017

**TABLE 2** Main topographical and vegetation characteristics of the study site.

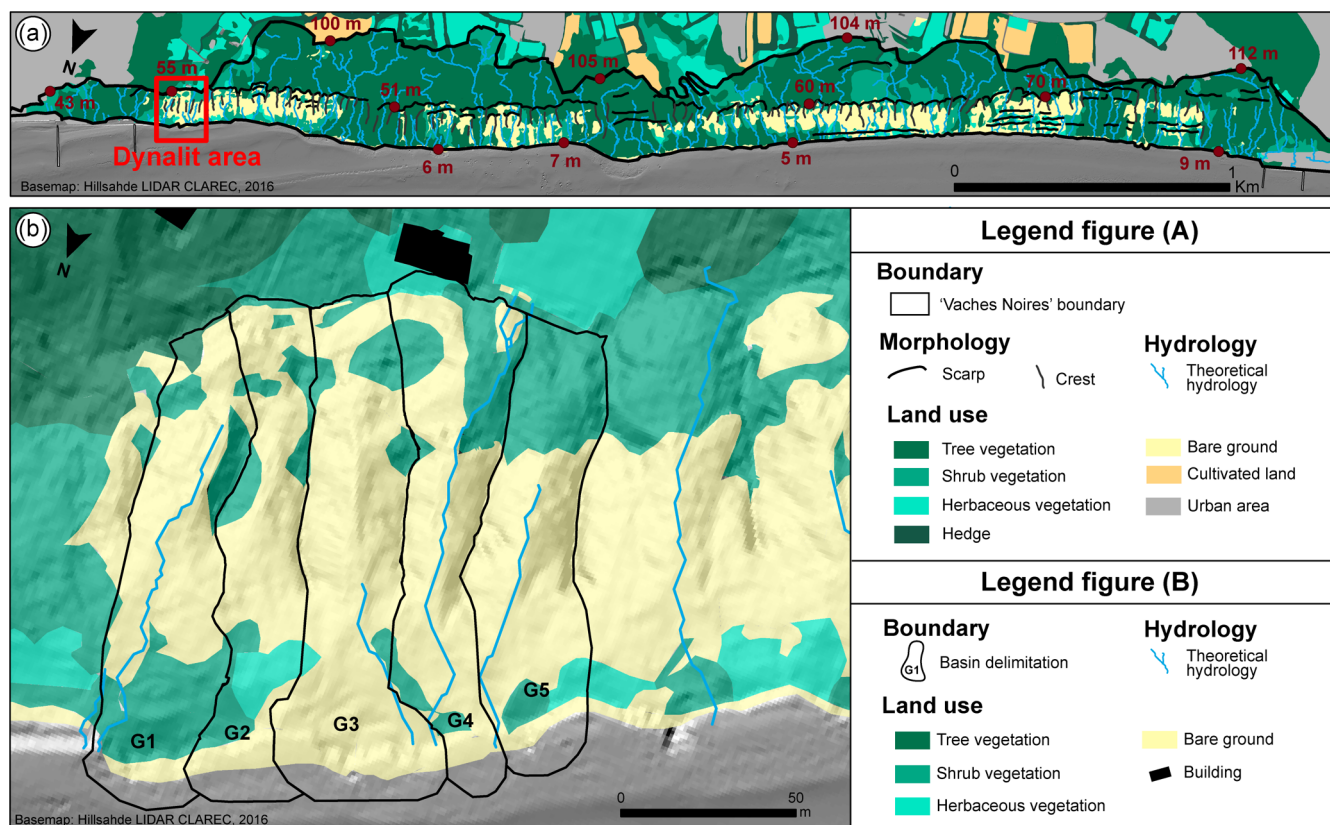
	Min	Max	Mean	STD	
Main Scarp Alt. (m)	43	112	66	8	
General slope (°)	17	32	25	3	
Land Use (%)	Tree vegetation	0	97	20	27
	Shrub vegetation	0	69	26	17
	Herbaceous vegetation	0	82	29	20
	Bare ground	1	69	26	17

The hydrographic network is dense, and the slope profile along the axis of the gullies is concave, with an average slope of approximately 25°. The badland surfaces are composed of clay-marl formations (Callovo-Oxfordian), overlain by a sandy-chalky series from the Albian-Cenomanian (Dugué, Fily, & Rioult, 1998). Normandy has a temperate oceanic climate. The Vaches Noires cliffs receive 700 to 900 mm of rainfall annually. According to the climate normals (1981–2010) at the Météo-France station in Saint-Gatien-des-Bois (15 km from the Vaches Noires cliffs), monthly rainfall can reach 100 mm in winter and 30–40 mm in summer. Temperatures range from 10°C to 20°C, with minima between 0°C and 10°C (Roulland et al., 2019).

### 3 | METHODOLOGY

#### 3.1 | Sampling

Water samples were collected from five gullies located at the eastern end of the Vaches Noires cliffs (Figure 1), specifically at the cliff base. The gullies, labelled G1 to G5, were selected as they represent the only accessible areas along the cliffs on the eastern side, where instrumentation could be installed. A total of 229 water samples were collected between 2017 and 2019, primarily following extended periods of rainfall or heavy rain events (Figure 1). The samples may originate from individual gullies—43 from G1, 2 from G2, 34 from G3, 44 from G4 and 11 from G5—or from confluences of two or three gullies at the same outlet: G1G2 (23 samples), G1G3 (9 samples), G2G3 (2 samples), G3G4 (15 samples), G4G5 (23 samples) and G3G4G5 (23 samples). Not all gullies generate runoff; this depends on precipitation events, leading to variability in the results (Data S1, Data S2, and Data S3). The duration required to fill one litre of water was recorded to estimate the water flow. A strong variability in runoff intensity was observed during runoff events, with significant changes in water flow between the beginning and end of sampling periods. Due to this variability, the sampling frequency was adjusted to every 30 minutes. However, samples from 2017 up to January 2018 were collected at a frequency of once per event, which explains the lack of information on standard deviations in the figures presented in the results section. Additionally, sources of suspended particulate matter (SPM) were sampled along the cliffs between G2 and G3 (Figure 1), as these locations are representative of the lithology found in the 87 gullies (Roulland et al., 2022). For each sample, parameters such as solid mass, sediment concentration, water flow, sediment fluxes, sediment yield and bulk organic geochemical analyses were measured (Data S1).



**FIGURE 2** Land-cover typology for the entire cliff system (a) and of the study area (b).

### 3.2 | Flux calculations

Since the pilot site cannot be continuously instrumented, the following calculations should be considered as a preliminary approximation of the SPM fluxes delivered by these gullies. Specifically, these fluxes (in g/s or t/y) were calculated by multiplying the concentration of each sample by the corresponding water flow. The total fluxes were then obtained by integrating the data from the years 2017, 2018 and 2019 across the different studied gullies (both individual and combined) (Data S2). Fluxes were extrapolated to encompass the entire cliff system (87 gullies) by considering land cover defined through an analysis of vegetation types, which include bare rock, herbaceous plants, shrubs or trees (Figure 2 and Table 2). The flux attributed to each gully corresponds to the flux of the gully with land cover characteristics most similar to those of the five studied gullies (Data S4). Theoretical combinations of gullies were established using runoff data obtained with the “hydrology” tool (ArcGIS). Similarly, the flux attributed to these combinations corresponds to the flux of the combination with characteristics closest to those of the studied gullies. Annual fluxes were then calculated, incorporating rainfall data by multiplying the fluxes by the number of hours of recorded rainfall in the area, as measured by a rain gauge. Finally, the fluxes were converted into tons per year (t/y). To calculate the TOC fluxes, the TOC data (%) were multiplied by the SPM flux (Data S3). However, these values represent only a first approximation, potentially underestimated, of the actual fluxes from the cliffs. Indeed, sampling could only be carried out in a limited area of five gullies, which have a lower elevation than the westernmost end of the cliffs, which could not be monitored.

Additionally, the sediment flux from mass movements at the base of the cliffs was estimated using differential analysis of photogrammetric models between January 30th, 2017 and November 19th, 2019. Following the protocol described by Medjkane et al., 2018, the 16 models derived from the Structure from Motion (SfM) method achieve from centimetre to decimeter resolutions (Kouah et al., 2024; Roulland, 2022). The volume of sediment obtained for the five gullies was used to estimate the total volume of sedimentary material eroded across the entire cliff system (Data S5). Gullies with tree cover at the cliff base were excluded from the calculations, as no lateral transport was observed in aerial photographs. The tree cover increases surface rugosity, which significantly limits surface processes.

The overall suspended particulate matter (SPM) flux for the Vaches Noires cliffs is the sum of the SPM flux and the sediment flux from mass movements. The global cliff yield is calculated by dividing this total flux by the surface area of the Vaches Noires cliffs involved in erosion (62.62 ha).

### 3.3 | Bulk organic geochemical characteristics

Organic Carbon (OC) and the quality of Organic Matter (OM), including the richness in hydrogen, oxygen and the labile/refractory nature of the OC, were analysed using the Rock-Eval 6 pyrolysis method (see details in Lafargue, Marquis, & Pillot, 1998; Copard et al., 2006; Baudin et al., 2015). This method involves a two-step process.

In the first stage, a crushed sample (50–80 mg), previously dried at 40°C in an air oven, is pyrolysed under an inert atmosphere. The temperature is increased from 200°C to 650°C at a rate of 25°C/min.

During this step, hydrocarbons (HC), CO<sub>2</sub> and CO emitted during OM pyrolysis are continuously quantified. Hydrocarbons are measured using a Flame Ionization Detector (FID), while CO<sub>2</sub> and CO are quantified with Infrared (IR) cells. These measurements are used to calculate the amount of OC released during OM pyrolysis (PC).

In the second stage, to achieve complete thermal degradation of the OM, the pyrolysis residue is oxidized in an air flow between 400°C and 750°C at a rate of 25°C/min. During this phase, CO and CO<sub>2</sub> are continuously measured by IR cells. These gases originate from both the decomposition of carbonates and the residual OM. The combustion of OM, which releases CO<sub>2</sub> and CO, allows for the determination of residual organic carbon (RC), which is considered to be more resistant to surface processes.

In this study, the following parameters were utilized:

- Total Organic Carbon (TOC in wt.%): This parameter is the sum of pyrolysed organic carbon (PC) and residual organic carbon (RC) obtained from the oxidation stage. TOC is considered representative of particulate OC (Copard et al., 2018).
- Oxygen Index (OI in mg CO<sub>2</sub>/g TOC) and Hydrogen Index (HI in mg HC g<sup>-1</sup> TOC): These indices provide information on the degree of oxidation and hydrogenation of the organic matter (Espitalié, Deroo, & Marquis, 1985; Lafargue, Marquis, & Pillot, 1998).
- Residual Carbon (RC in wt.%): RC is considered to be more refractory than PC (Peters, Walters, & Moldowan, 2005; Sanei, Stasiuk, & Goodarzi, 2005; Taylor, Teichmuller, & Davis, 1998). The RC/TOC

ratio serves as a good estimate of the recalcitrance and persistence of OC in the environment.

- S<sub>2</sub> Fraction (mg HC/g sediment): This fraction includes larger thermally cracking molecules of hydrocarbons derived from kerogen (Lafargue, Marquis, & Pillot, 1998).

## 4 | RESULT

### 4.1 | Geochemical parameters

The geochemical parameters from each SPM and source sample have been plotted as a function of gullies (Figure 3) and seasons (Figure 4), providing key fingerprints on the origin and recalcitrance of OM. When the HI index is high and the OI index is low, the OM is more sensitive to decomposition processes. Conversely, weathered OM is characterized by a high OI index and a low HI index. Most OI values fall between 100 mg CO<sub>2</sub>/g TOC and 250 mg CO<sub>2</sub>/g TOC. Some SPM samples exhibit OI values over 250 mg CO<sub>2</sub>/g TOC, while two source samples reach nearly 600 mg CO<sub>2</sub>/g TOC. HI values generally range from 50 mg HC/g TOC to 100 mg HC/g TOC. Some samples exhibit lower HI values, between 25 mg HC/g TOC and 50 mg HC/g TOC, including some source samples. Ten samples show higher HI values, ranging from 150 mg HC/g TOC to 350 mg HC/g TOC. When plotting S<sub>2</sub> vs. TOC values (Figures 3 and 4), most points fall between 0.15 and 1.00 wt.% for TOC values and 0.15 and 0.80 mg

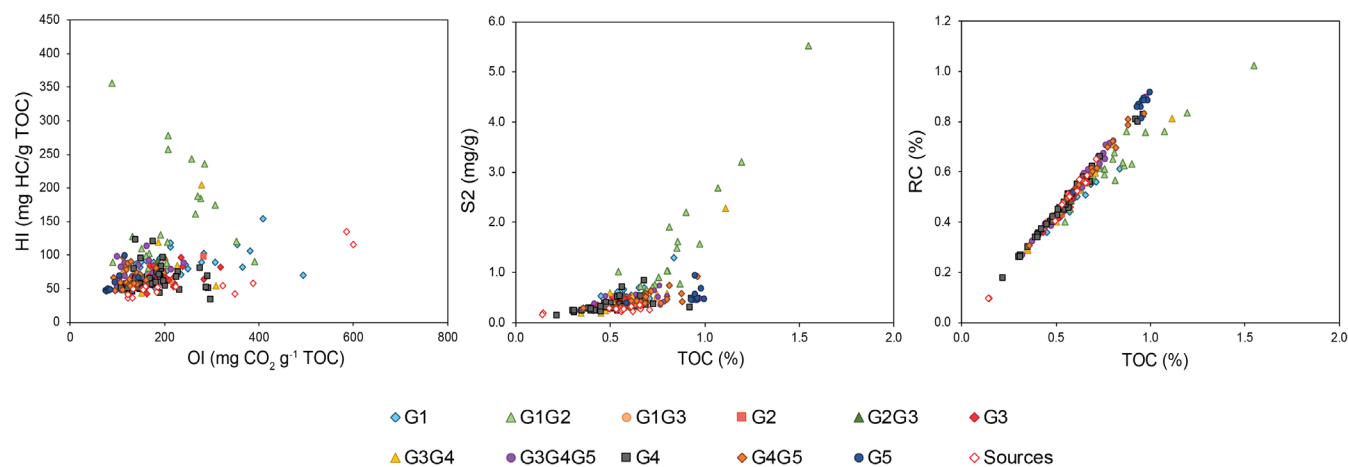


FIGURE 3 Geochemical parameters from Rock-Eval pyrolysis as a function of gullies.

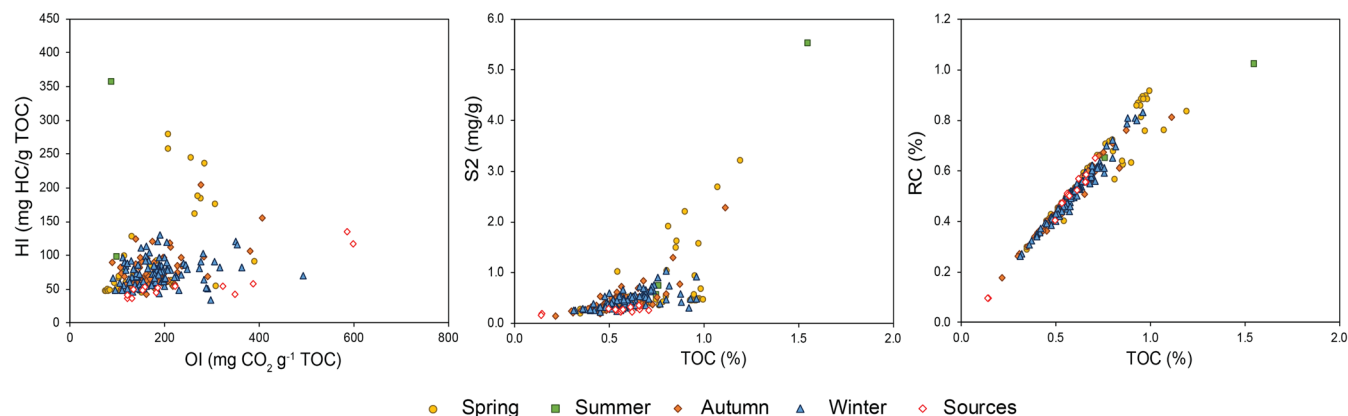
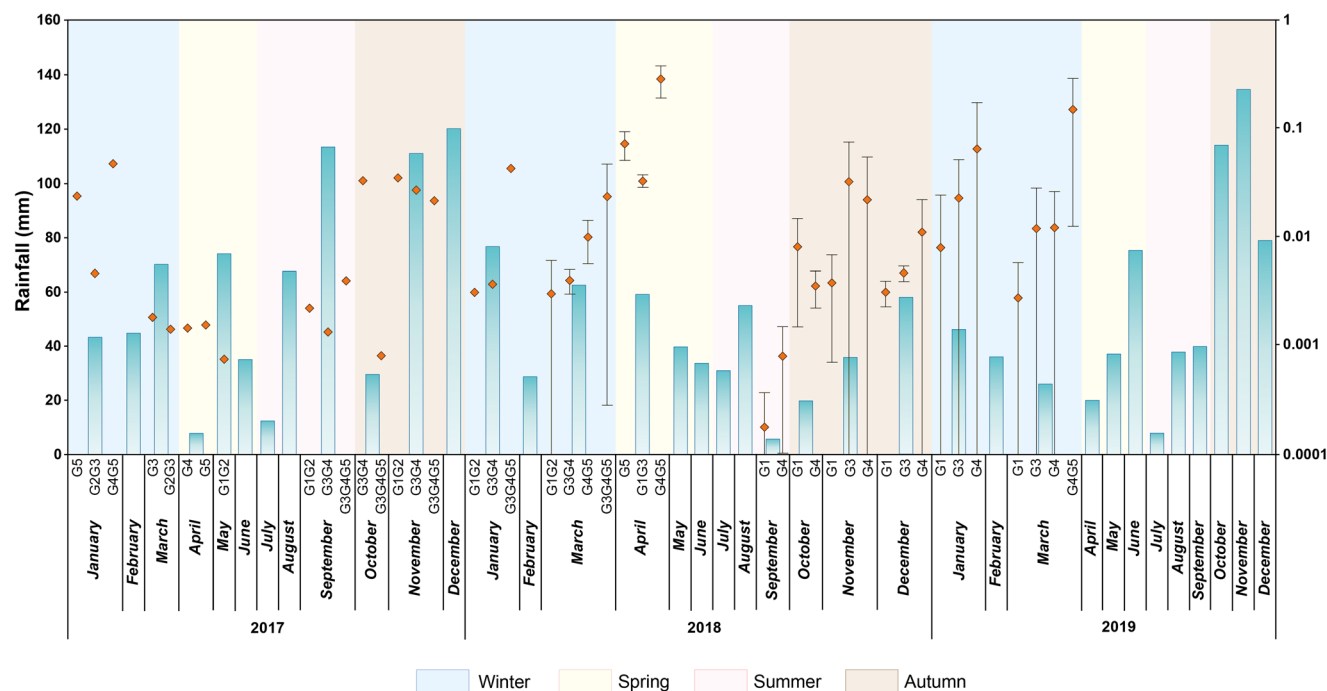


FIGURE 4 Geochemical parameters from Rock-Eval pyrolysis as a function of seasons.





**FIGURE 6** Evolution of TOC fluxes between spring 2017 to winter 2019 (the average values are represented by orange points, box-plots in blue).

**TABLE 3** SPM and TOC fluxes and yield as a function of the year.

	Year	Hours of rain	SPM flux (g/s)	SPM flux (t/y)	TOC flux (g/s)	TOC flux (t/y)	SPM yield (t/ha/y)	TOC yield (t/ha/y)
Studied gullies	2017	237.00	25.79	22.00	0.21	0.18	13.10	0.11
	2018	158.40	95.53	63.76	0.58	0.39	37.14	0.23
	2019	222.90	44.66	35.84	0.28	0.22	21.33	0.13
Entire cliff Extrapolation	2017	237.00	267.23	228.00	2.26	1.93	3.64	0.03
	2018	158.40	436.67	291.45	2.78	1.86	4.63	0.03
	2019	222.90	200.13	160.59	1.20	0.96	2.56	0.02

**TABLE 4** Cliff foot erosion, accumulation and sediment budget between 2017 and 2019.

Year	Sediment erosion (m <sup>3</sup> )	Sediment accumulation (m <sup>3</sup> )	Sediment budget (m <sup>3</sup> )	3-year budget (m <sup>3</sup> )	Study site		Entire cliffs (extrapolation)	
					Sediment flux (t/y)	Sediment yield (t/ha/y)	Sediment flux (t/y)	Sediment yield (t/ha/y)
2017	373 ± 53	312 ± 90	61 ± 105	392 ± 81	336 ± 70	4,688 ± 971	26,875 ± 5,568	16,797 ± 3,480
2018	353 ± 30	425 ± 49	-71 ± 57					
2019	563 ± 75	160 ± 43	403 ± 86					

Mean rock density (kg/m<sup>3</sup>): 2570 - Mean cliff foot surface (study site): 0.1 ha - Mean cliff foot surface (entire cliffs): 1.6 ha.

area) and (iii) other river systems exhibiting high erosion rates and consequently high suspended particulate matter (SPM) fluxes, such as Small Mountainous Rivers (SMRs) mainly located in active tectonic regions. Finally, we discuss the origin of the OC based on geochemical analyses performed on the samples.

### 5.1 | Sedimentary fluxes and production

According to a research report by Landemaine & Cerdan (2017), the sediment flux of the Seine River is estimated at  $4.9 \pm 2.9 \times 10^5$  t/y.

Lesourd (2000) estimated an annual sediment flux between  $6.0 \times 10^5$  and  $7.0 \times 10^5$  t/y, and Dubrulle et al. (2007) reported a mean annual mass of SPM close to  $6.0 \times 10^5$  t/y (Table 1). The Seine watershed area is about  $7.9 \times 10^6$  ha, so based on previous literature, the sediment yield of the Seine can be estimated between  $0.062 \pm 0.004$  t/ha/y and  $0.089$  t/ha/y. According to Vilmin et al. (2015), the yield of the Seine in the estuary was modelled at  $6.96$  t/km<sup>2</sup>/y, or  $0.069$  t/ha/y.

Although the sediment fluxes from gully erosion are significantly less than those of the Seine (considering the area difference: 70 ha vs 7,900,000 ha, respectively), the sediment yield of the badlands (global

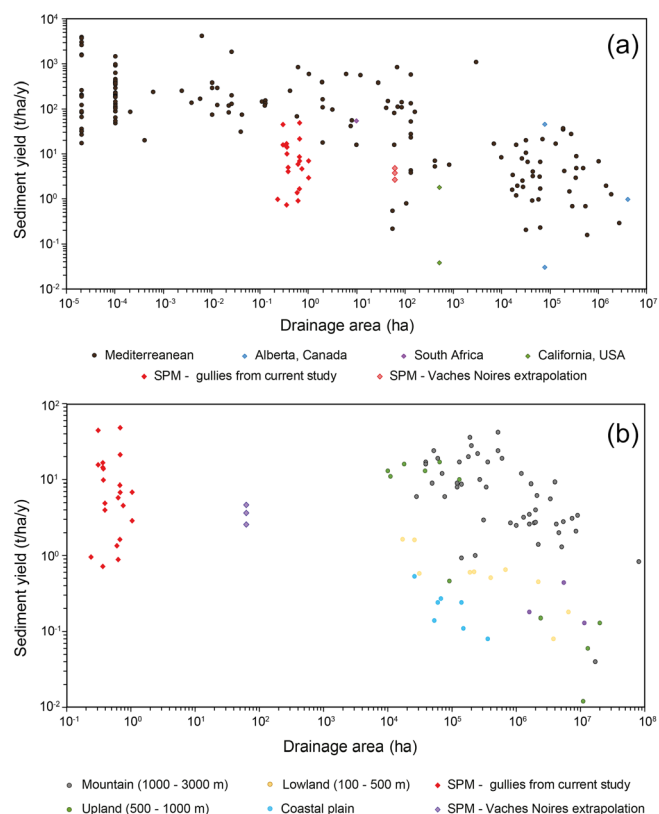
cliff: 3.62 t/ha/y) is 40 to 60 times higher than that of the Seine River. If we consider an SPM yield of about 24 t/ha/y (study area), the sediment yield of the badlands is 270 to 390 times higher than that of the Seine River. The cliff foot erosion is approximately 27,000 t/y, with a yield of around 16,800 t/ha/y (Table 3, Figure 7). These sediment losses generally correspond to the sliding of large blocks due to coastal erosion at the cliff foot. Therefore, it is expected to obtain significantly higher values compared to the gullies. The sediment yield is over 4,000 times greater than that of the coastal gullies from the same cliffs.

When the yield from these badlands is compared with other small rivers from Normandy, a similar observation can be made: the sediment yield from the badlands is on average 30 times greater than that of nearby coastal rivers (Maquaire, Detourbe, & Coudray, 2019, Figure 7), and 200 times greater when considering the sediment yield of the specific study area.

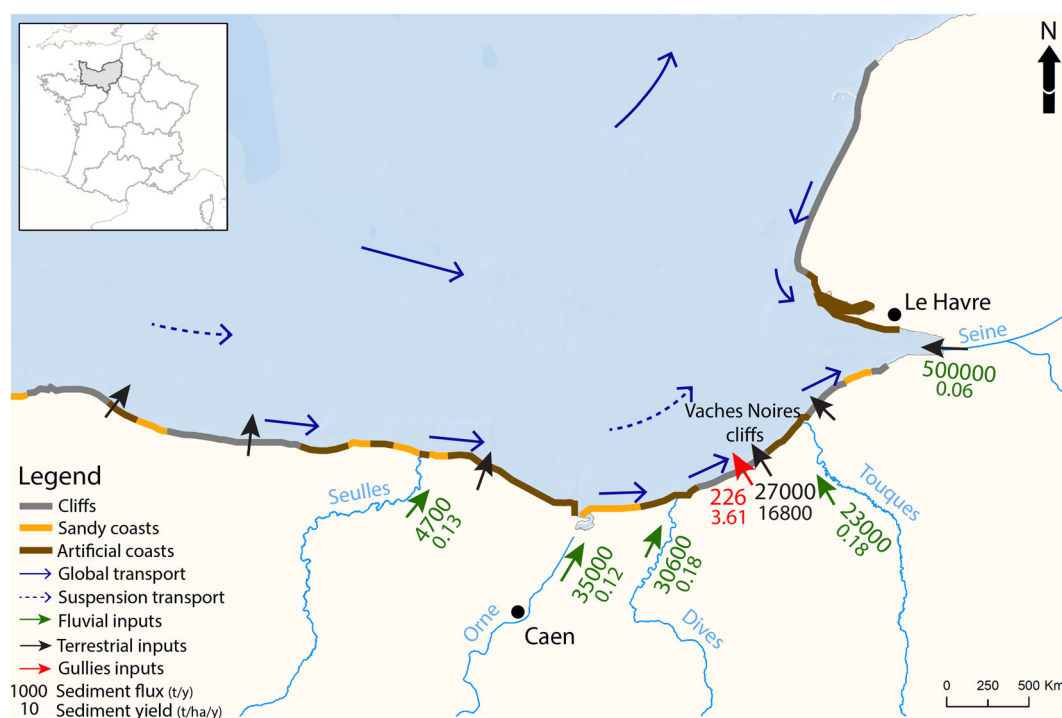
The review by Nadal-Romero et al. (2011) examined over 150 sediment yield data points from badlands around the Mediterranean area (Figure 8a).

When compared with these data, and with those from different geographic locations such as Alberta, Canada (Bryan & Campbell, 1980; Campbell, 1977, 1992), California, USA (Glancy, 1988) and South Africa (Keay-Bright & Boardman, 2009), the sediment yield of the Normandy badlands is globally lower than those reported in the literature. Regarding the gullies in this study, although the drainage area is similar to badlands in Tunisia, Spain and southern France, the sediment yield values are generally lower. Intense rainfall events are known to cause significant sediment mobilization in Mediterranean badlands. However, the average yield values for gullies extrapolated to the entire Vaches Noires cliffs are similar to those for the same area around the Mediterranean Sea. Despite the challenges in accurately monitoring sediment fluxes in such environments and

the potential biases in our calculations and extrapolations for the entire Vaches Noires cliffs, the pioneer data we present are quite comparable to other results (Figure 8a). Cliff foot erosion remains by far the dominant surface process releasing sediments to the English



**FIGURE 8** Comparison of sediment yield data from coastal badlands at the “Vaches Noires” cliffs with worldwide badlands (a) and global small mountainous rivers (SMRs) (b).



**FIGURE 7** Synthetic map of the seine estuary, showing sediment fluxes and sediment yields from small local coastal rivers (green), compared with inputs from coastal badlands at the “Vaches Noires” cliffs (red).

Channel. Badlands cliffs may exhibit a significant erosion and in the context of global change. Between 1826 and 2012, the retreat of the Vaches Noires cliffs is estimated to be between 0.10 and 0.15 m/year (Maquaire, Detourbe, & Coudray, 2019). According to Duguet et al., 2021, contemporary chalk cliffs in Normandy have experienced an increase of 33 to 57% in their retreat rates compared to long-term retreat rates. With respect to global change, which is triggering a global sea level rise and an increase in the occurrence of storms in these areas (Bricheno et al., 2023), cliff foot erosion is also likely to increase in the next decades. As a matter of fact, and as previously observed at a regional scale (Costa et al., 2019), these surface processes will cause significant impacts on Human society living along this land-to-sea frontier (surface management, relocation of inhabitants, etc.) that may lead to the implementation and/or reinforcement of coastal erosion protection by stakeholders. These protective structures can reduce or stop the sediment flux from the cliffs.

The comparison of coastal badlands with Small Mountainous Rivers (SMRs) was made using data from Milliman & Syvitski (1992), who compiled 280 data points from rivers worldwide that discharge into the ocean (Figure 8b). Although the drainage areas are much smaller in the case of the badlands studied here, the yields obtained are of the same order of magnitude as those of SMRs. In northwest Europe, French coastal gullies from the Vaches Noires behave similarly to the SMRs from mountainous (1,000–3,000 m) and upland environments (Figure 8b). Some gullies from the Vaches Noires cliffs exhibit even higher sediment yields. This high gully yield is attributed to the lithology of poorly cohesive rocks (clay marls). Until this study, no data existed in the literature for coastal plains with such small drainage areas as the Vaches Noires.

## 5.2 | TOC fluxes and carbon origin

Based on the relationship between source materials and SPM geochemical features, three samples were identified as the primary sediment sources for the five gullies located in the eastern part of the cliffs (Figures 3 and 4). The first source is the *Loph*a clays located in the central zone of the cliff, the second is “weathered rocks” hosting weathered organic matter with high OI values (>500 mg CO<sub>2</sub>/g TOC) found in the upper part of the cliff and the last source exhibits the highest HI values with relatively low OI values (88 mg CO<sub>2</sub>/g TOC). The SPM points influenced by this third source were collected from the most vegetated gully during spring/summer when vegetation is most active, suggesting that this source represents recent biospheric organic matter, these values are also typical from topsoils containing fresh biological material (OL soil horizons, Sebag et al., 2016). The sample with the highest HI value (357 mg HC/g TOC) can serve as a representative for this theoretical source. The set of SPM can thus be explained by a combination of “rock” and “vegetation” end-members. However, the latter source contributes poorly to the global OC flux and can be considered locally where the vegetation is more fully developed at the footstep (gullies G1 and G2). By understanding the origin of the organic carbon, it can be used as a transport tracer for further investigations into carbon sinks at the frontier between land and sea (e.g., Seine estuary).

TOC fluxes can vary over time, with the highest values occurring in autumn, winter and spring coinciding with peak runoff in the gullies

(Figure 6). Fossil OC can be preserved during transport, particularly when associated with clays which enhance the preservation of organic matter in ocean sediments (Blattmann et al., 2019). Scheingross et al. (2019) demonstrated that sediment transport plays a minimal role in POC oxidation, with few losses occurring during fluvial transport. This is especially relevant in the context of coastal badlands such as the Vaches Noires cliffs, where the transport time is very short. Since the gullies are located on the coast, oxidation during transport is either nonexistent or negligible. Consequently, fossil OC produced by the highly erodible surfaces of coastal badlands is transported from west to east due to longshore currents (Figure 7) and enters the Seine estuary where it can be trapped. Due to its recalcitrant nature—having undergone a rock cycle—this OC may be stored for the long term in the muddy deposits of the Turbidity Maximum Zone (TMZ) and could significantly contribute to the carbon budget in the Seine estuary.

From the perspective of the carbon cycle, several studies have enhanced our understanding of the role estuaries play in the global carbon cycle, highlighting that these interfaces can act both as carbon sources and sinks (Bianchi, 2006; Bianchi & Allison, 2009). This underscores the complexity of organic carbon origins, their fluxes, storage capacities and transformations within these biochemical reactors. There remains a notable gap in data regarding the lateral fluxes of POC from continental sources to the land-to-sea continuum (Bianchi & Allison, 2009; Canuel & Hardison, 2016). In the specific context of the Seine estuary, POC inputs come from two primary sources: common riverine sediment discharge and sediment from the erosion of adjacent coasts. Sediments from badlands carry a distinct organic signature that can be traced in oceanic and estuarine sediments, making them valuable for tracking sources within these environments.

## 6 | CONCLUSION

Over a three-year period, sediment and particulate organic carbon fluxes, as well as the yield of the Jurassic badlands in Normandy, were investigated. These coastal badlands provide sedimentary peak productivity during winter and autumn, characterized by harsher meteorological conditions and minimal vegetation cover. This study provides an initial estimate of sediment and particulate organic carbon fluxes from this highly productive area, where sediment yields are comparable to those observed in other global badlands and small mountain river systems.

In the Seine Bay, the sediment yields from these coastal badlands are significantly higher than those from the Seine River, with the estuary acting as a sink for these materials. Despite the ephemeral nature of runoff, coastal badlands function as a hotspot for organic carbon originating from local continental sources, contributing substantially to sediment and organic carbon inputs in the Seine Bay and the English Channel. On a European scale, coastal badlands exhibit sediment yields that are lower, yet comparable to those of the average European badlands. Considering the anticipated impacts of climate change—including rising sea levels and increased frequency of extreme weather events—monitoring such areas is essential for sustainable coastal management. The projected increase in erosion rates is expected to enhance the contribution of fossil organic carbon from

badlands to the lateral carbon transport from land and rock coasts to the English Channel and the Seine estuary.

## AUTHOR CONTRIBUTIONS

Alissia Rieux: c, d, e, f, g, h, i.

Yoann Copard: a, b, c, d, e, g, h.

Olivier Maquaire: a, b, c, d, e, g, h.

Thomas Roulland: d, e, f, h.

- a. conceptualization;
- b. funding acquisition;
- c. methodology (including methodological development);
- d. investigation (e.g. data collection);
- e. resources (provision of data etc);
- f. software (its provision and development);
- g. supervision;
- h. writing – initial draft;
- i. writing – reviewing and editing.

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