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From Carbon Sinks to Carbon Sources: A Regime Shift Induced by the Desiccation of Floodplain Lakes

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Abstract

Climate-driven hydrological changes are transforming river valleys, particularly floodplain lakes (FLs). Increasingly prolonged droughts and reduced flooding are causing the desiccation of oxbow and floodplain lakes, leading to the conversion of aquatic sediments into soils. This study investigates both the quantity and quality of carbon in these environments by analysing submerged sediments and sediments transformed into soils in small FLs of the Middle Vistula Valley (central Poland). Samples from eight FLs, representing both submerged and desiccated zones, were analysed for total organic carbon (TOC), humic substances (HSs), fulvic acids (FAs), humic acids (HAs), and carbonates ($CaCO_3$). The TOC content averaged about 40 g kg^{-1} in both sediments and soils, indicating considerable carbon storage. However, the proportion of FA and HA was low (3–4 g kg^{-1}, or 12–15% of TOC), suggesting a low degree of humification and a predominance of labile, easily degradable organic compounds susceptible to microbial mineralization and CO_2 emission. $CaCO_3$ content was also low (<1%), implying minimal potential for carbonate-derived CO_2 release. These findings confirm that drying FLs represent transitional systems and may shift from carbon sinks to carbon sources under ongoing climatic change. They also emphasize the need for more focused research on these, until now, underestimated ecosystems.

Keywords: oxbow lakes; fulvic acids; humic substances; carbonates; shallow lakes; small water bodies

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1. Introduction

The topic of climate change is widely discussed in both global and local contexts. In many regions, including Central Europe, shifts in weather and climate patterns are leading to prolonged droughts, declining groundwater levels, and an increased frequency of extreme rainfall events [1,2]. Extended drought periods alternating with short but even intense rainfall events are reshaping river valleys and causing the desiccation of floodplain lakes (FLs). The consequences of such hydrological extremes are not yet fully understood [3,4]. Sediments of FLs, which previously functioned as aquatic deposits, are

now rapidly transforming into soils. Studying carbon in these transforming sediments is crucial for understanding their role in greenhouse gas emissions, soil fertility, and the mobilisation of pollutants, which have important environmental implications [5,6]. Prior to climatic changes, FLs functioned as complex components of the environment, existing as independent water bodies periodically inundated by river waters. Changes in water levels on the floodplain terraces drive continuous exchanges of sediments, nutrients, organic matter, pollutants, and organisms between the FLs, river, and the floodplain. Therefore, FLs play important roles as regulators of floods, repositories of pollutants, and refuges for biodiversity, including bird habitats [7]. FLs have always undergone natural cycles of drying and transformation into terrestrial ecosystems; however, the current scale and rate of desiccation are unprecedented. This process is accelerated by human activities: artificial regulation of river flow, construction of reservoirs, and changing climatic conditions—all of which pose significant threats to the existence of FLs [4]. In recent years, cases of oxbow lake desiccation have been reported in various climatic zones and geographic regions around the world: in the boreal zones of Alaska [5], in the humid continental climate of Wisconsin, north-eastern USA [8], in the south-western Bolivian Amazon Basin (tropical climate) [9], and in the subtropical monsoon climate of the Yangtze Floodplain in China [10]. Gmitrowicz-Iwan et al. [6] reported that in the Middle Vistula Valley, Central Europe (humid continental climate), the total surface area of FLs declined by nearly 31% between 2017 and 2020.

In recent years, the role of inland water bodies in carbon sequestration has been increasingly recognized. Although they cover a much smaller portion of the Earth's surface than oceans, approximately 2% compared to 71% of oceans, inland waters accumulate nearly three times more carbon annually than marine systems. Among the most effective natural tools for carbon dioxide (CO_2) removal are lakes, particularly eutrophic ones, where photosynthetic activity by aquatic organisms consumes CO_2, while sedimentary carbon storage provides an additional complementary mechanism for climate regulation [11]. Studies by Ghosh et al. [12] indicate that oxbow lakes can function as effective carbon sinks while exhibiting relatively low methane emissions, highlighting their potential importance for climate change mitigation. [12]. It is important to note that this sequestration mechanism differs from the oceanic photosynthetic CO_2 incorporation, which operates on a global scale; both processes are complementary in regulating the carbon cycle. However, under newly developed dry and aerobic conditions, the amount of carbon stored in the surface layer of sediments transformed into soil decreases. The pool of CO_2 previously absorbed through photosynthesis also declines [5]. Marcé et al. [13] and Paranaíba et al. [14] point out that dry inland waters, particularly sediments from former lakes, may become significant sources of carbon emissions, with CO_2 and CH_4 fluxes exceeding those observed in surrounding soils. This process can contribute to the intensification of the greenhouse effect.

Not only organic but also inorganic carbon compounds may undergo transformation. In lakes located in temperate climate zones, the water is often rich in calcium–magnesium–bicarbonate ions ('hard water') and tends to precipitate $CaCO_3$, particularly during the summer months [15]. Sediments stored beneath a water layer typically exhibit near-neutral pH. However, once lakes dry out, the sediments are subjected to different processes. In a humid climate, soil leaching often occurs, leading to a decrease in pH. Under acidic conditions, $CaCO_3$ may decompose, releasing CO_2 into the atmosphere [16]. In addition to pH reduction, sediment desiccation may alter redox conditions and affect microbial activity [5]. Altogether, these factors may result in the activation of previously immobilized contaminants, as sediments often serve as significant reservoirs of pollutants. River, reservoir and FL sediments often contain considerable amounts of heavy metals and organic pollutants, for example, polychlorinated biphenyls, chlorobenzenes and DDTs [17–

19]. They remain largely isolated from the environmental cycle when buried under a water layer with a near-neutral pH. However, once contaminated sediments dry out and become exposed, these pollutants can be remobilized and reintroduced into the environment. On the other hand, under highly moist and anoxic conditions, the formation of stable metal sulfides may be enhanced [20].

The qualitative composition of carbon can strongly influence this process. TOC accumulated in sediments is mainly composed of HS, including HA, FA, and humin. HS are a heterogeneous group of dark-colored, polydisperse organic compounds that constitute the majority of organic carbon in sediments and soils, with over 70% of carbon present in this highly reactive and recalcitrant form. They play a key role in facilitating the microbial oxidation of toxic organic compounds and organic acid salts. They also act as electron shuttles between microorganisms and pollutants, for example, by reducing heavy metals and organic contaminants [21,22]. HS can be divided into HA, FA, and humins based on their solubility. HAs are soluble in alkali but precipitates at low pH, and FA remains soluble at all pH values. Both fractions are highly reactive, contribute to soil fertility, and influence the physical, chemical, and biological properties of soils [23]. Therefore, from the perspective of climate change and carbon sequestration, the total amount of TOC is critical, whereas the qualitative composition is crucial for assessing the potential release of pollutants.

Once dried, lakes, including floodplain waterbodies, may be converted into agricultural areas, primarily meadows and pastures [24,25], and can unintentionally become point sources of pollution. Heavy metals and other contaminants may enter plants and subsequently affect the entire food chain. This demonstrates that the amount and composition of carbon in sediments can affect both greenhouse gas emissions, through microbial activity, and the mobilisation of pollutants, by influencing their chemical binding and mobility in the environment. It underscores that carbon is a fundamental element, playing a crucial role in the functioning of both sediments and soils. However, current environmental protection programs and legislation, such as the European Union Water Framework Directive [26], do not consider FLs as separate monitoring units.

Our study aims to analyse the quantity and quality of carbon in drying small FLs and to compare sediments from their deeper parts, which remain permanently submerged, with sediments from shallow, dried areas that have functioned as soils for four years. It remains unclear how these newly exposed soils function and how different environmental conditions affect the amount and quality of organic carbon in these two materials, and consequently, the functioning of the ecosystem and carbon storage in such environments. The hypothesis to be tested is that sediments from the dried parts of FLs contain higher amounts of TOC and carbonates. The conducted research may help identify potential environmental risks and highlight the need for regulatory attention to these transitional ecosystems. The analyses provide evidence of an actual climatic effect, not model-based predictions, but a tangible change in ecosystem functioning and in the transformation of sediments into soils. The presented data on the content and forms of carbon are essential for modelling the carbon balance on both regional and global scales and for improving the understanding of the carbon cycle.

2. Materials and Methods

2.1. Study Area and Environmental Context

The research was conducted in the Middle Vistula Valley, located in central Poland (Figure 1), in a temperate continental climate zone with a warm summer subtype (Dfb) according to the Köppen climate classification [27]. The Vistula is one of the last large natural rivers in Europe that has preserved a largely natural character along significant stretches of its course. Although embankments along most sections of the river restrict the

active floodplain to about 1 km in width, the Vistula still maintains a relatively natural and unconfined flow. In its upper course, the river exhibits meandering patterns, whereas in the middle and lower sections, the channel divides into smaller branches that later reconnect, giving the river a braided character. Numerous islands and sandbars occur within the channel system. The embanked floodplain contains many oxbow and floodplain lakes, most of which are elongated and narrow, aligned parallel to the river course. Some of these water bodies maintain a permanent connection with the main channel, while others are completely isolated. During periods of high water caused by intense rainfall or snowmelt, the entire floodplain may become inundated, with water and sediments transported by the Vistula spreading across the valley floor.

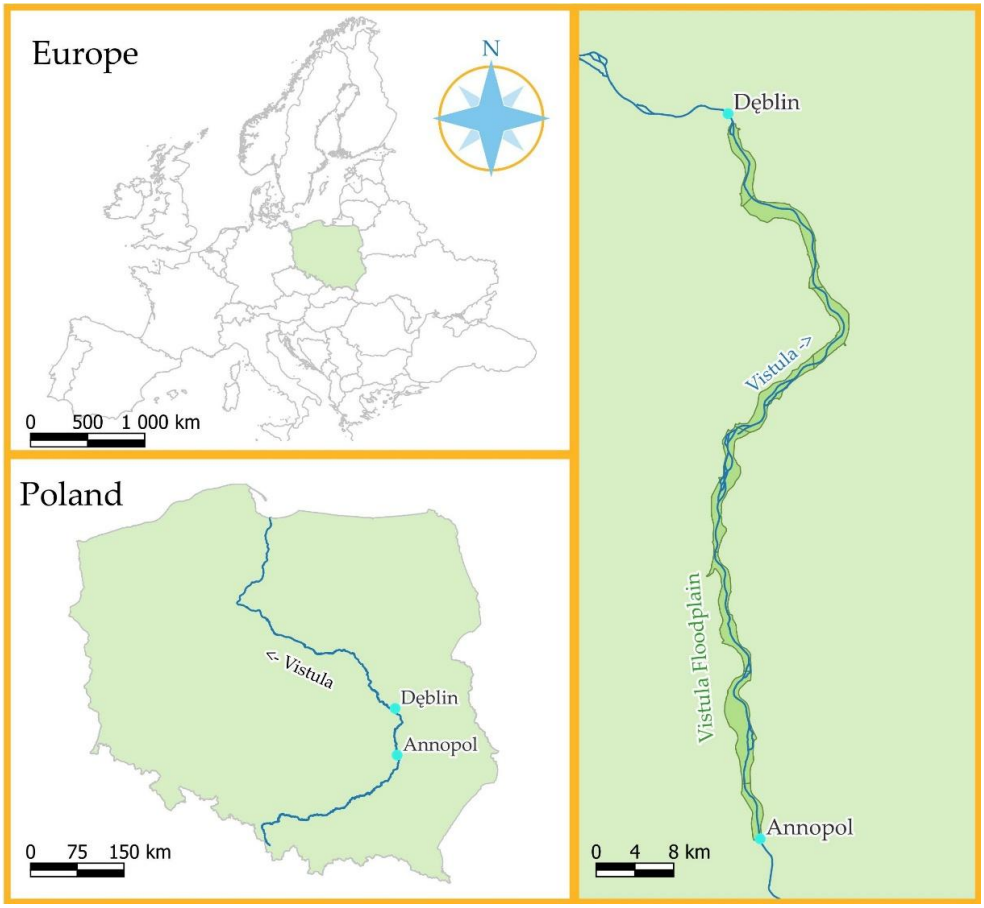


Figure 1. Study area—the Vistula Valley.

However, due to recent climatic and hydrological changes, the flooding events have become increasingly rare. Historically low water levels have been recorded almost every year. This has resulted not only in the drying of parts of the main river channel but also in the desiccation of floodplain water bodies. According to Gmitrowicz-Iwan et al. [6], between 2017 and 2020, the total surface area of floodplain lakes within the studied 100 km section of the Vistula decreased by nearly 31%, from 565 ha in 2017 to 391 ha in 2020. After 2020, the problem of drought in the Vistula catchment intensified further, leading to continued desiccation of both the main river channel and adjacent water bodies. Meteorological data indicate that mean annual air temperatures have been steadily increasing, reaching record highs in recent years. The average for 1991–2010 was 8.43 °C, for 2011–2020 it rose to 9.33 °C and for 2021–2024 it was 9.78 °C, which illustrates a clear warming trend. In 2024, the mean annual temperature reached 10.9 °C (Figure 2). Meanwhile, total annual precipitation in this period has not changed significantly, averaging around 600 mm per year; however, its seasonal distribution has changed. Prolonged dry spells are

becoming more frequent, while rainfall events are now short but highly intense, often leading to flash floods [28].

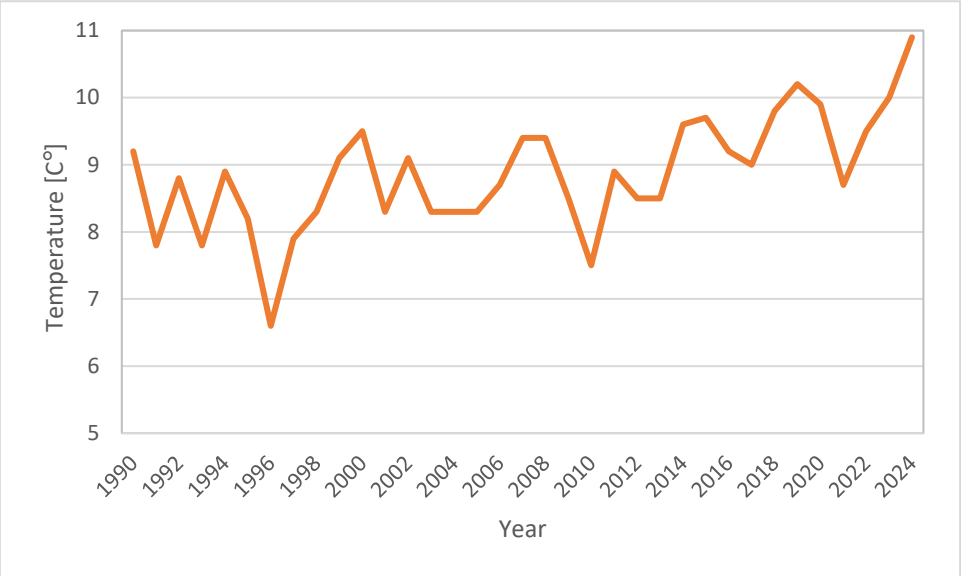


Figure 2. Mean annual air temperatures in Poland in 1990–2024 (based on the data published by the Institute of Meteorology and Water Management—National Research Institute, Poland [28]).

2.2. Sampling and Analysis

Eight small and shallow FLs were selected for analysis (Figure 3). They were remnants of former, larger oxbow lakes (sections of the old river channel). The lakes were elongated, situated within the active floodplain, approximately parallel to the river, each covered an area of less than 10,000 m^2, and their maximum depth was 4 m. Satellite image analysis indicated that the surface area of these FLs remained relatively stable between 2010 and 2017. However, after 2017, the water bodies in the Vistula Valley underwent significant desiccation. The selected FLs were lakes consisting of both permanently submerged areas (active lakes) and sections that had remained dry since 2018, i.e., sediments that have transformed into soils, in the early stages of pedogenesis. From 2018 to 2022, monthly monitoring of the lakes confirmed that these sections no longer functioned as sediments but rather as soils, with no groundwater table present down to a depth of 30 cm, except during high-water events and floodplain inundations, which occurred a few times per year or not at all in some years (e.g., in 2019). Samples of both materials were collected in November 2022.

Figure 3. Drying floodplain lake.

To ensure precise sampling from permanently dry and active areas, sampling points were pre-planned in random yet regularly spaced locations and determined using a GNSS device (Figure 4). Sampling near the water-soil contact zone was avoided. Both materials were collected from the uppermost, most active layer (0–15 cm). Soil samples were collected using Egner's Cane soil, while sediments were sampled with a Kajak sampler. Individual soil samples from each lake were combined to produce a single bulk sample of approximately 5 L, and the same procedure was applied to the sediments. This resulted in eight sediment samples and eight soil samples.

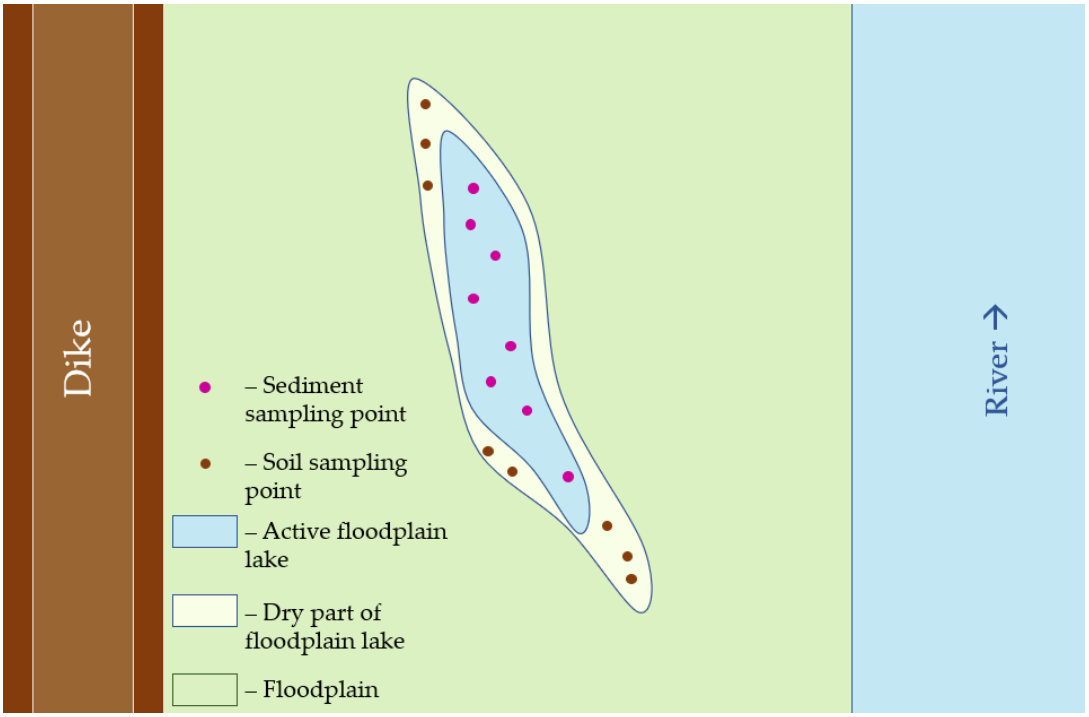


Figure 4. Sampling scheme.

The samples were air-dried, and plant residues, stones, and other debris were removed. They were then ground in a mortar and sieved through a 2 mm sieve. The prepared material was used for subsequent analyses. Particle size distribution was determined using sieving and sedimentation method [29], with fractions classified as sand (0.05 mm), silt (0.002–0.05 mm), and clay (<0.002 mm) [30]. Soil pH in KCl and H_2O was measured potentiometrically using an Elmetron CX-705 device (Elmetron, Zabrze, Poland). Carbon fractions were determined based on differences in solubility. The contents of HA and FA were analysed following a procedure based on solubility differences in acidic and alkaline solutions [31,32]. Samples were mixed with 0.1 M NaOH at a 1:10 ratio. After 24 h, a sample of the solution was taken for the determination of HS content. The remaining solution was then acidified with H_2SO_4 to pH 2 and heated to precipitate HA. The fraction of FA was determined in the remaining solution. TOC and its fractions were measured using a TOC analyser (TOC-VCSH, Shimadzu Corp., Kyoto, Japan) [33]. The $CaCO_3$ content was determined using the Scheibler method [34]. All analyses were performed in triplicate.

2.3. Statistical Analysis

To compare differences in the mean values of TOC, HS, FA, HA, and $CaCO_3$ contents, both between sediments and soils within individual FLs and across all studied lakes, an analysis of variance (ANOVA) was applied. Prior to performing ANOVA, the normality of the data was assessed using the Shapiro–Wilk test, and homogeneity of variance was confirmed. Pairwise comparisons of means were performed using the post hoc Least Significant Difference (LSD) test and Tukey's test at a significance level of $p < 0.05$. Correlation relationships between the texture and contents of TOC, HS, FA, HA, and $CaCO_3$ in sediments and soils were determined using Pearson's correlation analysis. All statistical analyses were carried out using the Statistica 13.3 software package [35]. An AI tool (ChatGPT) was used to assist in translating parts of the original draft from Polish to English.

3. Results

Significant differences were found in the contents of TOC, HS, HA, and $CaCO_3$ between sediments and soils when all lakes were considered together (Table 1). The average TOC content in the analysed lakes was 40.50 g kg^{-1} in sediments and 42.37 g kg^{-1} in soils, while the median values were 17.69 g kg^{-1} and 47.89 g kg^{-1}, respectively (Figure 5). The highest sedimentary TOC content was recorded in Lake 7 (129.86 g kg^{-1}), whereas the lowest occurred in Lake 2 (6.80 g kg^{-1}). For soils, the corresponding values were 67.86 g kg^{-1} in Lake 1 and 9.88 g kg^{-1} in Lake 2. Lake 7 exhibited the largest difference in TOC content between sediment and soil, with 74.35 g kg^{-1} more TOC in the sediment. Conversely, Lake 6 showed the greatest difference in favour of the soil, with a 36.95 g kg^{-1} higher TOC content compared to the sediment. The smallest differences between sediment and soil TOC contents were observed in Lakes 2 and 5. Statistical analysis revealed significant differences in TOC content in soils among all lakes, except for Lakes 2 and 5. In sediments, TOC also differed significantly among lakes, except for the pairs Lakes 4 and 5 and Lakes 4 and 6, where the differences were not statistically significant. The results presented in Tables 1 and 2 show significant variability in the soils and sediments of the FL along the studied section of the river, especially in the case of TOC content.

Table 1. Summary of one-way ANOVA results assessing differences in the contents of the studied components among the eight floodplain lakes, presented separately for sediments and soils.

		Unit	F-Ratio	Significance Level *p*
sediments	TOC	g·kg^{-1}	**7151.68**	<0.05
	HS		**5923.57**	<0.05
	FA		**8746.21**	<0.05
	HA		**738.88**	<0.05
	HS	%TOC	**47.29**	<0.05
	FA		**62.18**	<0.05
	HA		**81.04**	<0.05
	$CaCO_3$	%	**773.23**	<0.05
soil	TOC	g·kg^{-1}	**6366.27**	<0.05
	HS		**122.82**	<0.05
	FA		**2240.06**	<0.05
	HA		**115.29**	<0.05
	HS	%TOC	**238.26**	<0.05
	FA		**582.68**	<0.05
	HA		**68.07**	<0.05
	$CaCO_3$	%	**176.27**	<0.05

Notes: Statistically significant results at the $p < 0.05$ significance level are shown in bold. TOC—total organic carbon, HS—humic substances, FA—fulvic acids, HA—humic acids, $CaCO_3$—carbonates.

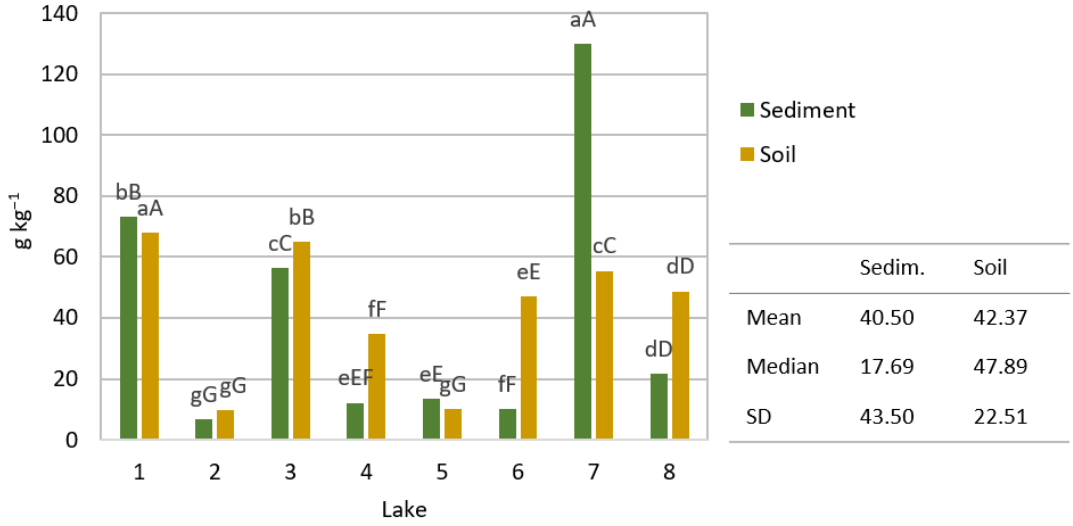


Figure 5. Average TOC content [g kg^{-1}] in sediments and soils, and the difference between sediments and soils for each lake. Means that share the same letters do not differ significantly. Lowercase letters (a, b, c…) indicate differences according to the LSD test; uppercase letters (A, B, C…) indicate differences according to Tukey's test. Comparisons were performed within each material (i.e., separately among sediments or among soils). SD is standard deviation (For detailed data, see Table A1).

The average content of HS in the studied lakes was 9.04 g kg^{-1} in sediments and 9.89 g kg^{-1} in soils. Similarly, the percentage of HS in TOC was higher in sediments than in soil samples. The highest HS weight content in sediments was observed in Lake 7 (23.46 g kg^{-1}), while the lowest occurred in Lake 2 (2.02 g kg^{-1}). In soils, the highest content was recorded also in Lake 7 (19.08 g kg^{-1}) and the lowest in Lake 5 (6.47 g kg^{-1}). The largest difference in HS content between sediments and soils was found in Lake 6, with 6.37 g kg^{-1} of HS more in the soil. The smallest difference was observed in Lake 1, with sediments containing only 0.19 g kg^{-1} more than the soil. Lake 4 exhibited the highest percentage of

HS in TOC in sediment samples (55.80%), while the lowest proportion was recorded in Lake 1 (16.39%). For soil samples, the highest and lowest values were found in Lake 2 (67.15%) and Lake 3 (14.11%), respectively. The largest differences in the percentage of share of HS in TOC between sediments and soils were observed in Lakes 2 and 5 (favouring soils) and Lake 4 (favouring sediments), whereas the smallest difference occurred in Lake 1, with less than 1% HS more in the soil (Table 2). The HS content in sediments differed significantly among all lakes, except for Lakes 5 and 6. In contrast, in soils these differences were less pronounced than in sediments, with fewer of them reaching statistical significance. Regarding the percentage share of HS in TOC, a greater number of statistically significant differences were observed in soils, while fewer significant differences were identified in sediments.

Table 2. Average HS content in sediments and soils and the difference between sediments and soils across all lakes.

Lake	HS [g·kg^{-1}]			HS [%TOC]		
	Sed.	**Soil**	**Dif.**	**Sed.**	**Soil**	**Dif.**
1	11.98 b B	11.79 b B	0.19	16.39 e E	17.37 de CD	−0.98
2	2.02 h G	6.62 f EF	−4.60	29.67 d CD	67.15 a A	−37.47
3	10.60 c C	9.17 cd CD	1.43	18.74 e E	14.11 e D	4.63
4	6.68 e E	7.40 ef DEF	−0.71	55.80 a A	21.29 cd C	34.51
5	3.60 g F	6.47 f F	−2.87	26.38 d DE	63.64 a A	−37.27
6	3.89 f F	10.26 c BC	−6.37	38.72 c BC	21.83 c C	16.89
7	23.46 a A	19.08 a A	4.38	18.07 e E	34.37 b B	−16.31
8	10.07 d D	8.35 de DE	1.72	46.43 b AB	17.12 e CD	29.30
mean	9.04	9.89	−0.85	31.27	32.11	−0.84
median	8.38	8.76	−0.26	28.02	21.56	1.82
SD	6.88	4.14	3.56	14.47	21.43	27.80

Notes: Means sharing the same letters do not differ significantly: small letters (a, b, c…)—LSD test; capital letters (A, B, C…)—Tukey's test; values were compared within each column; HS—humic substances, Sed.—sediments, Dif.—difference, SD—standard deviation.

The average content of FA was higher in soils, amounting to 4.10 g kg^{-1}. Similarly, the average share of FA in TOC was higher in soils, reaching 13.41%. The highest FA content in both sediments and soils was observed in Lake 7 (10.54 g kg^{-1} and 7.44 g kg^{-1}, respectively), while the lowest values were recorded in Lake 2 (0.61 g kg^{-1} in sediments and 2.63 g kg^{-1} in soils). Regarding the percentage share of FA in TOC, the highest value in sediment samples was found in Lake 4, and in soil samples in Lake 5 (24.09% and 28.02%, respectively). The lowest values were observed in Lake 1 (6.17% in sediments) and Lake 3 (6.00% in soils). In Lake 1, the average FA content in sediments and soils was identical (4.51 g kg^{-1}), with the difference in the percentage of FA in TOC less than 0.5% in favour of the soil. The largest differences in FA content between sediments and soils were observed in Lake 6 (3.19 g kg^{-1} higher in soils) and Lake 7 (3.10 g kg^{-1} higher in sediments). In Lake N. 5, the percentage of FA in TOC was 20.46% higher in soils than in sediments (Table 3). The FA content differed significantly among lakes in both sediments and soils (except for soils of lakes 1 and 6). When analysing the percentage share of FA in TOC, not all differences among lakes were statistically significant; however, the number of significant differences was clearly higher for soils than for sediments.

Table 3. Average FA content in sediments and soils and the difference between sediments and soils across all lakes.

Lake	FA [g·kg^{-1}]			FA [%TOC]		
	Sed.	Soil	Dif.	Sed.	Soil	Dif.
1	4.51 c C	4.51 b B	0.00	6.17 e D	6.64 ef D	−0.47
2	0.61 h H	2.63 g G	−2.02	9.01 d CD	26.65 b A	−17.64
3	4.90 b B	3.90 c C	1.01	8.67 d CD	6.00 f D	2.67
4	2.89 e E	3.33 e E	−0.44	24.09 a A	9.60 d C	14.49
5	1.03 g G	2.85 f F	−1.82	7.57 de D	28.02 a A	−20.46
6	1.27 f F	4.46 b B	−3.19	12.60 c C	9.49 d C	3.10
7	10.54 a A	7.44 a A	3.10	8.12 de D	13.41 c B	−5.29
8	4.26 d D	3.65 d D	0.61	19.64 b B	7.48 e D	12.16
mean	3.75	4.10	−0.34	11.98	13.41	−1.43
median	3.58	3.78	−0.22	8.84	9.55	1.10
SD	3.22	1.51	1.99	6.48	8.90	12.63

Notes: Means sharing the same letters do not differ significantly: small letters (a, b, c…)—LSD test; capital letters (A, B, C…)—Tukey's test; values were compared within each column; FA—fulvic acids, Sed.—sediments, Dif.—difference, SD—standard deviation.

The mean content of HA was higher in the soil samples, amounting to 4.39 g kg^{-1}. The mean percentage of HA in TOC was also higher in the soil, reaching 15.27%. The highest HA concentrations were recorded in Lake 7, both in sediment and soil samples (6.09 g kg^{-1} and 8.55 g kg^{-1}, respectively). In contrast, the lowest HA content in sediments was observed in Lake 2 (1.30 g kg^{-1}), while the lowest value in soils occurred in Lake 5 (2.91 g kg^{-1}). The highest percentage of HA in TOC among sediment samples was found in Lake 4 (25.32%), whereas the lowest occurred in Lake 7 (4.69%). For the soil samples, the highest proportion of HA in TOC was noted in Lake 2 (39.27%), and the lowest in Lake 8 (6.51%). Lake 2 showed the greatest difference (2.56 g kg^{-1}) in HA content between sediment and soil, with significantly higher values in the soil samples. The smallest difference was observed in Lake 8, where the sediment contained 0.51 g kg^{-1} more HA than the soil. Regarding the percentage of HA in TOC, the largest difference was again found in Lake 2, where the soil samples contained 20.13% more HA. The smallest difference (0.66%), also favouring the soil, was recorded in Lake 3 (Table 4). HA content differed significantly among sediments in most lakes, except for the pair of lakes 3 and 8. In soils, HA content exhibited less variation among lakes. Similarly, for the percentage of HA in TOC, the differences among lakes were less numerous in both sediments and soils. Overall, the results indicate substantial variability in HS, FA and HA content both between lakes and between sediments and soils, with no consistent pattern favouring either environment, suggesting that local conditions exert a stronger influence on carbon fractions distribution than the sediment soil transition itself.

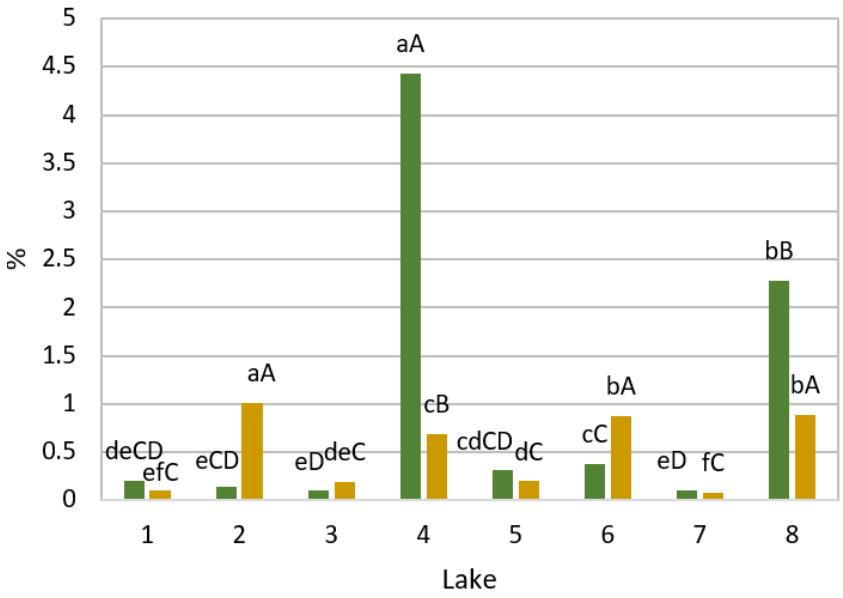
Table 4. Average HA content in sediments and soils and the difference between sediments and soils across all lakes.

Lake	HA [g·kg^{-1}]			HA [%TOC]		
	Sed.	Soil	Dif.	Sed.	Soil	Dif.
1	4.02 b B	4.89 b B	−0.88	5.49 d C	7.21 d D	−1.71
2	1.30 h G	3.86 c CD	−2.56	19.14 b B	39.27 a A	−20.13
3	3.45 d C	4.39 b BC	−0.94	6.09 d C	6.75 d D	−0.66
4	3.04 e D	3.61 cd CDE	−0.57	25.32 a A	10.39 d CD	14.93
5	2.07 g F	2.91 e E	−0.84	15.13 c B	28.69 b B	−13.55
6	2.53 f E	3.74 c CD	−1.21	25.17 a A	7.95 d D	17.21

7	6.09 a A	8.55 a A	−2.46	4.69 d C	15.40 c C	−10.72
8	3.68 c C	3.17 de DE	0.51	16.97 bc B	6.51 d D	10.47
mean	3.27	4.39	−1.12	14.75	15.27	−0.52
median	3.25	3.80	−0.91	16.05	9.17	−1.19
SD	1.45	1.79	1.00	8.51	12.23	13.80

Notes: Means sharing the same letters do not differ significantly: small letters (a, b, c…)—LSD test; capital letters (A, B, C…)—Tukey's test; values were compared within each column; HA—humic acids, Sed.—sediments, Dif.—difference, SD—standard deviation.

The mean percentage share of $CaCO_3$ was 1.00% in sediments and 0.51% in soils. However, it is important to note that the highest $CaCO_3$ shares in sediments were recorded in Lakes 4 (4.43%) and 8 (2.28%), while in the remaining lakes, sediment $CaCO_3$ content did not exceed 0.5%, with the lowest value observed in Lake 3 (0.10%). In soils, the highest $CaCO_3$ content was found in Lake 2 (1.01%), whereas the lowest occurred in Lake 7 (0.08%). The greatest differences in $CaCO_3$ content between sediment and soil were observed in Lakes 4 and 8, 3.74% and 1.39%, respectively. The smallest variations were noted in Lakes 7 (0.03%, higher in sediment) and 3 (0.09%, higher in soil) (Figure 6). $CaCO_3$ content did not vary greatly among the lakes. In both sediments and soils, many of the observed differences were not statistically significant.



	Sedim.	Soil
Mean	1.00	0.51
Median	0.26	0.45
SD	1.57	0.40

Figure 6. Average $CaCO_3$ content [%] in sediments and soils, and the difference between sediments and soils for each lake. Means that share the same letters do not differ significantly. Lowercase letters (a, b, c…) indicate differences according to the LSD test; uppercase letters (A, B, C…) indicate differences according to Tukey's test. Comparisons were performed within each material (i.e., separately among sediments or among soils). SD is standard deviation (For detailed data, see Table A2).

Significant differences were found in the contents of TOC, HS, HA, FA, and $CaCO_3$ between sediment and soil within individual lakes. Only in the case of HS and FA in Lake 1, and HS in Lake 8, the mean values in sediment and soil did not differ significantly (Table 5). In five cases (Lakes 2, 3, 4, 6, and 8), the TOC content was significantly higher in soils than in sediments. HS were significantly more abundant in the soils of four lakes (Lakes 2, 4, 5, and 6). FA showed significantly higher concentrations in the soils of Lakes 2–7, while lower FA content in soils compared to sediments was observed only in Lake 8. A similar pattern was found in HA, with lower HA levels recorded only in the soils of Lake 8 compared to its sediments. When comparing $CaCO_3$ content between sediments and

soils, significantly higher $CaCO_3$ concentrations were found in sediments of five lakes (Lakes 1, 4, 5, 7, and 8).

Table 5. Overview of the analysis of variance of the content of the studied substances in sediments and soils within individual lakes.

Lake No.	Compound	Unit	F-Ratio	*p*	Lake No.	Compound	Unit	F-Ratio	*p*
1	TOC	g·kg^{-1}	**133.14**	**<0.05**	5	TOC	g·kg^{-1}	**98.63**	**<0.05**
	HS		2.62	0.18		HS		**2265.38**	**<0.05**
	FA		0.02	0.91		FA		**3062.11**	**<0.05**
	HA		**8.48**	**0.04**		HA		**12.72**	**0.02**
	HS	%TOC	**27.45**	**0.01**		HS	%TOC	**388.45**	**<0.05**
	FA		**74.80**	**<0.05**		FA		**544.48**	**<0.05**
	HA		**13.92**	**0.02**		HA		**22.50**	**0.01**
	$CaCO_3$	%	**37.50**	**<0.05**		$CaCO_3$	%	**78.77**	**<0.05**
2	TOC	g·kg^{-1}	**63.97**	**<0.05**	6	TOC	g·kg^{-1}	**15,491.33**	**<0.05**
	HS		**9816.49**	**<0.05**		HS		**22,682.74**	**<0.05**
	FA		**2287.66**	**<0.05**		FA		**6863.29**	**<0.05**
	HA		**234.62**	**<0.05**		HA		**76.79**	**<0.05**
	HS	%TOC	**169.02**	**<0.05**		HS	%TOC	**888.37**	**<0.05**
	FA		**993.08**	**<0.05**		FA		**91.65**	**<0.05**
	HA		**42.07**	**<0.05**		HA		**848.32**	**<0.05**
	$CaCO_3$	%	**3072.73**	**<0.05**		$CaCO_3$	%	**43.70**	**<0.05**
3	TOC	g·kg^{-1}	**523.72**	**<0.05**	7	TOC	g·kg^{-1}	**66,951.02**	**<0.05**
	HS		**153.88**	**<0.05**		HS		**271.72**	**<0.05**
	FA		**423.37**	**<0.05**		FA		**2312.57**	**<0.05**
	HA		**106.22**	**<0.05**		HA		**191.71**	**<0.05**
	HS	%TOC	**373.46**	**<0.05**		HS	%TOC	**2172.68**	**<0.05**
	FA		**506.48**	**<0.05**		FA		**3505.77**	**<0.05**
	HA		**18.68**	**0.01**		HA		**1152.07**	**<0.05**
	$CaCO_3$	%	**784.00**	**<0.05**		$CaCO_3$	%	**40.50**	**<0.05**
4	TOC	g·kg^{-1}	**311.26**	**<0.05**	8	TOC	g·kg^{-1}	**2169.90**	**<0.05**
	HS		**104.08**	**<0.05**		HS		2.78	0.17
	FA		**252.70**	**<0.05**		FA		**122.67**	**<0.05**
	HA		**35.43**	**<0.05**		HA		**65.08**	**<0.05**
	HS	%TOC	**36.03**	**<0.05**		HS	%TOC	**159.06**	**<0.05**
	FA		**41.67**	**<0.05**		FA		**630.32**	**<0.05**
	HA		**37.43**	**<0.05**		HA		**372.92**	**<0.05**
	$CaCO_3$	%	**13,858.56**	**<0.05**		$CaCO_3$	%	**76.70**	**<0.05**

Notes: Statistically significant results at the $p < 0.05$ significance level are shown in bold. TOC—total organic carbon, HS—humic substances, FA—fulvic acids, HA—humic acids, $CaCO_3$—carbonates.

The effect of granulometric fractions on the content of TOC, HS, HA, FA, and $CaCO_3$ in both sediment and soil was not statistically significant. Therefore, the strongest relationship was observed between the clay fraction in the sediment and the percentage of HS in TOC within the sediment (r = –0.78)—the lower the clay content, the higher the HS (Table 6).

Table 6. Correlation coefficients between texture and the content of TOC, HS, HA, FA, and $CaCO_3$ in sediment and soil.

		Sediments			
		Unit	sand	silt	clay
Sediments	TOC	g·kg^{-1}	−0.37	0.21	0.53
	HS		−0.45	0.32	0.57
	FA		−0.45	0.32	0.58
	HA		−0.41	0.30	0.51
	HS	%TOC	0.24	−0.06	−0.43
	FA		0.02	0.15	−0.21
	HA		0.64	−0.47	−0.78 *
	$CaCO_3$	%	−0.06	0.23	−0.14
		Soil			
		Unit	sand	silt	clay
Soil	TOC	g·kg^{-1}	−0.66	0.58	0.69
	HS		−0.27	0.23	0.28
	FA		−0.24	0.19	0.28
	HA		−0.26	0.27	0.21
	HS	%TOC	0.57	−0.51	−0.59
	FA		0.61	−0.55	−0.61
	HA		0.49	−0.40	−0.56
	$CaCO_3$	%	0.22	−0.19	−0.24

Notes: * means statistically significant results at the $p < 0.05$ level. TOC—total organic carbon, HS—humic substances, FA—fulvic acids, HA—humic acids, $CaCO_3$—carbonates.

4. Discussion

The amount of TOC in the studied 0–15 cm layer of sediments and soils was approximately 40 g kg^{-1}, which is comparable to the values reported for Fluvisols in the Odra River valley (western Poland) by Kawałko et al. [36]. In that study, the top 0–10 cm layer of meadow soils contained about 50 g kg^{-1} TOC. Along the lower section of the Vistula River, the TOC values in Fluvisols (0–30 cm) under grassland use were substantially lower—26 g kg^{-1} [37] and 17 g kg^{-1} [38]. The contents of FA and HA in the materials we analysed were approximately 3 and 4 g kg^{-1}, respectively, for both sediments and soils. In comparison, the Odra valley Fluvisols contained about 10 and 12 g kg^{-1} of FA and HA, respectively [39], while in the lower Vistula valley these values reached approximately 5 and 8 g kg^{-1} [37]. The proportional contribution of these fractions to TOC was also lower in the present study—12% and 15%, respectively—compared with about 20% in the Odra valley and 19% and 31% in the lower Vistula. These differences indicate that the organic matter in the analysed section of the Vistula valley sediments and soils is characterized by a lower degree of humification and likely contains a higher proportion of labile, easily degradable organic carbon compounds that are more susceptible to microbial mineralization and CO_2 release. This may result from several environmental and geomorphological factors, including shorter soil development time in the recently dried floodplain zones, periodic rewetting, and low biological activity [5]. Moreover, the reduced content of FA and HA may indicate that the transformation of organic matter in these young soils is still at an early stage of pedogenesis, reflecting their transitional nature between sediment and soil environments.

Studies by Gmitrowicz-Iwan et al. [40] confirm that small oxbow lakes in this section of the Vistula River are hypereutrophic. Shallow eutrophic lakes generally exhibit a high carbon sequestration potential, meaning they bind and store large amounts of OC in their

sediments [11]. This is consistent with the results of the present study; both the analysed sediments and the sediments transformed into soils contained relatively high amounts of OC, averaging about 4%. However, the drying of these lakes leads to a shift from anaerobic to aerobic conditions. Patil et al. [5] demonstrated a significant decrease in TOC following the desiccation of floodplain lakes. In our case, the drying occurred only a few years earlier; therefore, a gradual decline in TOC content in the sediments transformed into soils can also be expected. This results mainly from increased CO_2 emissions from the dried sediments. Elevated emissions may be associated with a stronger coupling between CO_2 and gaseous fluxes in dry sediments that lack an overlying water layer, as well as with increased CO_2 production driven by greater oxygen availability, which stimulates overall microbial growth, including enzymatic activity [5,41,42].

Another factor that may contribute to increased CO_2 emissions from sediments is a high $CaCO_3$ content. When redox conditions shift and acidity increases, pH may decrease below neutral values, promoting the dissolution of $CaCO_3$ and the release of CO_2 [16]. However, in most natural floodplain sediments, such reactions are limited to strongly acidified environments (pH < 6). In the present study, both sediments and soils contained only small amounts of $CaCO_3$—mostly below 1%. Therefore, the potential CO_2 emissions resulting from carbonate decomposition are likely negligible.

Compared with sediments, the analysed soils were characterised by a higher proportion of silt and sand fractions and a lower clay content. The pH (in KCl) ranged from 5.13 to 7.83 in the sediments and from 5.02 to 7.24 in the soils. It shows that despite exposure, the pH values in sediments and soils remained similar, likely due to the relatively short period of four years since desiccation. Only the sediments from lakes 1 and 7, as well as the soils from lake 7, exhibited pH values below 6. When comparing individual FLs, pH values were generally lower in soils than in sediments. Moreover, soils contained higher amounts of TOC. The combination of a higher TOC content and lower pH may indicate a potential for release of accumulated contaminants from the exposed sediments. Previous studies by Gmitrowicz-Iwan et al. [19] demonstrated that FL sediments along this section of the Vistula River contain significant concentrations of heavy metals, particularly cadmium. This implies that newly exposed soils, following the desiccation of FLs and associated changes in redox conditions, may act as secondary sources of heavy metals and other pollutants.

Upon exposure to oxygen, sediments undergo substantial geochemical transformation. Liu et al. [43] showed that the periodic drying and rewetting process may lead to the oxidation of sulfides (e.g., FeS, FeS_2) and increased bioavailability of trace metals, especially lead and cadmium. Moreover, the decomposition of organic matter may further lower pH, increasing the solubility and mobility of metals. In particular, metals bound to organic matter or carbonate fractions can become remobilised under acidic and oxic conditions. Conversely, in well-aerated soils, the formation of iron and manganese oxides may lead to metal immobilization through adsorption or co-precipitation processes [18,44]. The net environmental impact depends on the balance between these opposing processes. Consequently, these transitional soils represent dynamic but unstable systems, where evolving physicochemical conditions determine whether they act as sinks or secondary sources of contaminants in the river valley ecosystem.

Numerous studies highlight the often underestimated importance of small lakes, including oxbow lakes, in the water cycle and ecosystem functioning [45,46]. They act as reservoirs of both organic carbon and contaminants, and their drying can enhance greenhouse gas emissions and trigger secondary pollution. At the same time, desiccated oxbows are frequently converted to agricultural land, primarily used as meadows and pastures. Such agricultural use may further alter the carbon and contaminant cycles. Therefore, an in-depth understanding of the properties of sediments transformed into soils and

the processes occurring within them is essential. Our results should serve as guidance for policymakers in the sustainable management of floodplain areas and land use planning. Inappropriate use of these soils may further contribute to increased CO_2 emissions and contamination of the food chain.

5. Conclusions

The drying and disappearance of FLs is a natural process, but their current scale and rate have been intensified by climate change. FLs are particularly sensitive to hydrological shifts, leading to the transformation of sediments into soils, a process still poorly understood. The studied sediments and sediments transformed into soils were rich in TOC (~40 g kg^{-1}), confirming their role as carbon reservoirs. However, the low share of HA and FA (3–4%) indicates a low degree of humification and a dominance of labile organic compounds prone to microbial degradation and CO_2 release. The generally low $CaCO_3$ content (<1%) suggests negligible carbonate-related emissions. The findings confirm the research hypothesis that FL soils contain higher amounts of OC and carbonates compared to sediments. However, the observed transformation of aquatic sediments into soils implies that TOC levels may decline over time due to enhanced microbial mineralization once FLs dry out. This highlights the need for continued monitoring of such transitional environments to quantify their role in regional carbon budgets. Further studies on drying FLs should be extended to other rivers and climatic zones, as climate change is driving hydrological transformations worldwide. Although small in size, FLs are numerous, and their cumulative effect may significantly influence global carbon balance.

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Data Availability Statement: The data generated in this study is available at https://zenodo.org/records/17559092 (accessed on 10.Nov.2025). DOI number of the dataset: https://doi.org/10.5281/zenodo.17559091.

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Abbreviations

The following abbreviations are used in this manuscript:

TOC	Total organic carbon
HS	Humic substances
HA	Humic acids
FA	Fulvic acids
FL	Floodplain lake
SD	Standard deviation

Appendix A

Table A1. Average TOC content [g kg^{-1}] in sediments and soils, and the difference between sediments and soils across all lakes.

Lake	TOC		
	Sed.	**Soil**	**Dif.**
1	73.12 b B	67.86 a A	5.25
2	6.80 g G	9.88 g G	−3.08
3	56.59 c C	65.01 b B	−8.41
4	12.21 e EF	34.75 f F	−22.53
5	13.67 e E	10.18 g G	3.48
6	10.06 f F	47.01 e E	−36.95
7	129.86 a A	55.51 c C	74.35
8	21.71 d D	48.77 d D	−27.05
mean	40.50	42.37	−1.87
median	17.69	47.89	−5.75
SD	43.50	22.51	34.28

Notes: Means sharing the same letters do not differ significantly: small letters (a, b, c…)—LSD test; capital letters (A, B, C…)—Tukey's test; values were compared within each column; TOC—total organic carbon, Sed.—sediments, Dif.—difference, SD—standard deviation.

Table A2. Average $CaCO_3$ content [%] in sediment and soil, and the difference between sediment and soil across all lakes.

Lake	$CaCO_3$ [%]		
	Sed.	**Soil**	**Dif.**
1	0.21 de CD	0.11 ef C	0.10
2	0.14 e CD	1.01 a A	−0.87
3	0.10 e D	0.19 de C	−0.09
4	4.43 a A	0.69 c B	3.74
5	0.31 cd CD	0.20 d C	0.11
6	0.38 c C	0.88 b A	−0.50
7	0.11 e D	0.08 f C	0.03
8	2.28 b B	0.89 b A	1.39
mean	1.00	0.51	0.49
median	0.26	0.45	0.07
SD	1.57	0.40	1.47

Notes: Means sharing the same letters do not differ significantly: small letters (a, b, c…)—LSD test; capital letters (A, B, C…)—Tukey's test; values were compared within each column; $CaCO_3$—carbonates , Sed.—sediments, Dif.—difference, SD—standard deviation.

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