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Distribution of Soil Organic Carbon in Riparian Forest Soils Affected by Frequent Floods (Southern Québec, Canada)

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Abstract: Measuring soil organic carbon (SOC) in riparian forest soils affected by floods is crucial for evaluating their concentration and distribution along hydrological gradients (longitudinal and transversal). Hydromorphological factors (e.g., sedimentation vs. erosion, size of floodplain, flood recurrence) may be the cause of major variations in the concentration of organic matter and SOC in soils and could have a direct impact on C levels in soil profiles. For this study, SOC concentrations were assessed in riparian soils collected along transects perpendicular to the riverbanks which cross through inundated and non-inundated zones. Other soil properties (e.g., acidity, nitrogen, texture, bulk density) that may affect the concentration of SOC were also considered. The main purpose of this study was to assess SOC concentrations in soils subjected to flooding with those outside the flood zones, and also measure various soil properties (in surface soils and at various depths ranging from 0 to 100 cm) for each selected area. Across the various areas, SOC shows marked differences in concentration and spatial distribution, with the lowest values found in mineral soils affected by successive floods (recurrence of 0–20 years). SOC at 0–20 cm in depth was significantly lower in active floodplains (Tukey HSD test), with average values of 2.29 $\pm$ 1.64% compared to non-inundated soils (3.83 $\pm$ 2.22%). The proportion of C stocks calculated in soils (inundated vs. non-inundated zones) was significantly different, with average values of 38.22 $\pm$ 10.40 and 79.75 $\pm$ 29.47 $t{\cdot}ha^{-1}$, respectively. Flood frequency appears to be a key factor in understanding the low SOC concentrations in floodplain soils subjected to high flood recurrence (0–20 years).

Keywords: soil organic carbon; floodplain soils; floods; hydroclimatic conditions; southern Québec

1. Introduction

Soils are one of the most significant reservoirs of soil organic carbon [1–3] and have the capacity to store carbon over very long periods of time (hundreds or even thousands of years) [3–5]. Soil carbon stocks are in fact a major indicator of atmospheric CO_2 exchanges, and soil can play a crucial role in the fight against global warming through its ability to store carbon [3–5]. In fact, several researchers have studied the capacity of soils to store carbon in various terrestrial environments (e.g., forests, prairies, and farmland) [6–8] and measured their variability based on land use [9–11]. Soil organic carbon can vary over space and time based on numerous soil conditions and soil-forming processes, including hydroclimatic and morphological factors [12–14]. The organic carbon content can also vary depending on the depth of the soil profile [8,15], and some physical soil properties such as texture, bulk density, drainage, water saturation, and leaching can also affect soil organic carbon content [15–18]. Lastly, various anthropogenic or natural disruptions such as deforestation, agricultural activities, and fires may, over the short and medium term, significantly impact the variability and content of soil organic carbon. For instance, forest cutting will cause a major loss of soil organic carbon, whereas afforestation can contribute to soil fertility [19,20]. If floods are seen as a soil fertility factor [21–23], an increase in flood frequency could cause a loss in organic matter on the soil surface and reduce their in situ C content [18,24–27].

The aim of this study was to analyze the spatial distribution of SOC for soils subjected to frequent flooding in different basins and sub-basins in southern Québec (e.g., Coaticook, Eaton, Massawippi rivers). The intent of the study was to provide a better understanding of SOC content in riparian environments affected by frequent flooding. To determine the effect of floods on soil development and the capacity of floodplain soils to store organic carbon, we considered two specific flood recurrence zones (intervals of 0–20 years and 20–100 years) delineated by the flood-risk maps of government and municipal agencies. Sites located in no-flood zones (NFZ) but near riverbanks were also studied for comparative purposes. Other key soil properties were analyzed, including pH, texture, bulk density, total nitrogen (TN), and Fe + Al content. The SOC content and other soil properties were measured at different layer depths in order to better assess their variability in soil profiles. Our main assumption was that the increase in flood frequency observed over the past decades [28,29] affects the accumulation of surface litter and depletes the soil in carbon, thus affecting soil quality and fertility.

2. Materials and Methods

2.1. Study Area

The study area is located in south-central Québec (Figure 1), which is characterized by many rivers, several of which are subject to frequent and heavy flooding. The Coaticook, Massawippi, and Saint-François rivers, in particular, may experience flooding every two to four years, on average, depending on snow and rain conditions. The mean annual flow of the Coaticook, Eaton, and Saint-François rivers, for instance, can attain a maximum average discharge of 131, 222, and 1087 m^3/s, with peak discharges of 223, 418, and 2080 m^3/s [30]. The maximum flow recorded from 1925 to 2002 in the Drummondville area is 2719 m^3/s [30]. The river section between Drummondville and Sherbrooke is subject to frequent floods, especially since the 1970s [28,29], and frequent flood zones are characterized by large floodplains covered with uneven-aged forests. The woodlands in this region occupy about 60–70% of the surface areas, followed by farmland (15–20%), with the remainder consisting of urban areas, watercourses, and wetlands (10–12%) [31]. Large plains or low terraces dominate the banks of the rivers being studied, and are characterized by ancient or recent alluvial sediments, at times interspersed with rocky outcrops. Glacial deposits, glaciolacustrine sediments, or reworked glacial till are also found at higher elevations [32]. The floodplain soils are part of the Cumulic Regosol (CU.R) and Gleyed Cumulic Regosol (GLCU.R) subgroups in the Canadian System of Soil Classification, while the no-flood zones are mainly characterized by brunisolic and podzolic soils [33]. Lastly, this region is characterized by a humid continental climate with average annual precipitation of 1113.5 mm, with deviations varying depending on the time of year (69 mm in March and 106 mm in July) [34]. The average annual temperature recorded between 1981 and 2010 is 6.4 °C, with high temperatures in July (monthly average of 20.9 °C) and low temperatures in January (−10.2 °C monthly average).

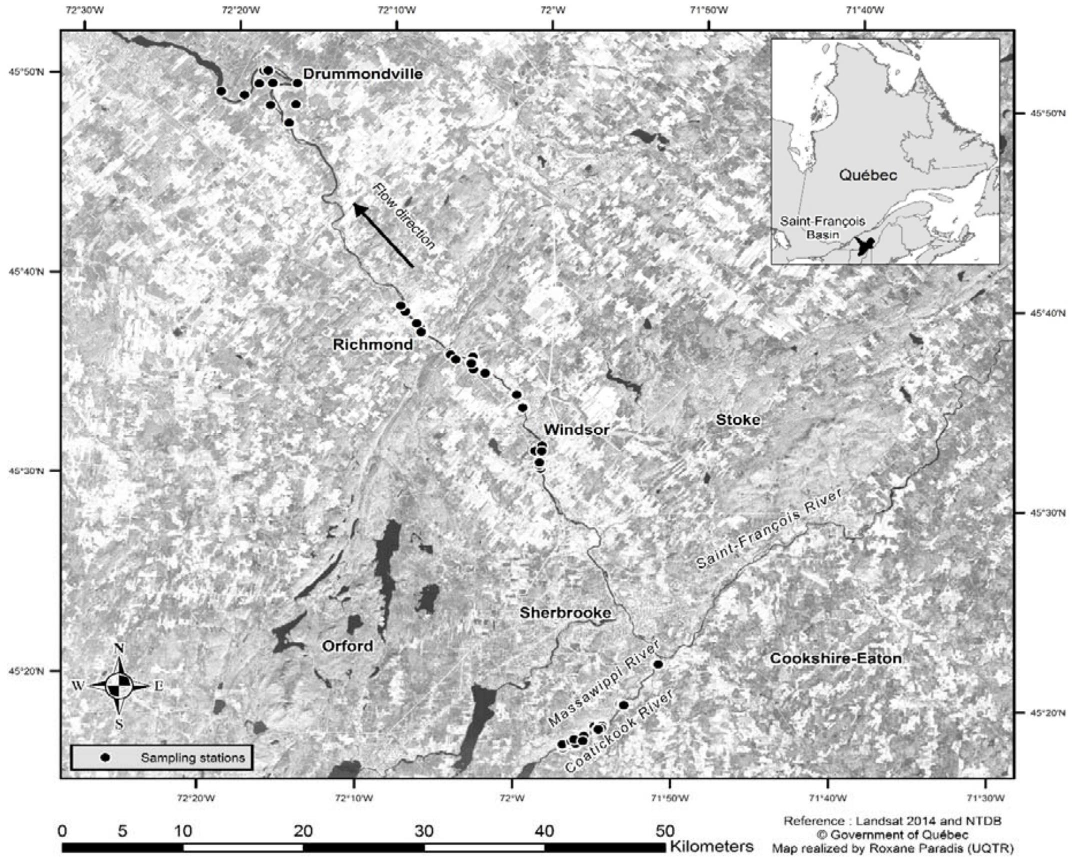

Figure 1. Location of sampling sites in the basins and sub-basins of different rivers in Southern Québec, Canada. The sites are distributed in the two flood zones (recurrence intervals of 0–20 years and 20–100 years) and outside the floodplains. The sampling sites are located mainly along Coaticook, Massawippi, and Saint-François rivers.

2.2. Sampling Sites

All the soil sampling sites were located in wooded areas along the riverbanks and were spread out in the flood zones, i.e., two flood-risk zones, one with a flood recurrence interval of 0–20 years (FFZ: frequent flood zone) and another with a flood recurrence interval of 20–100 years (MFZ: moderate flood zone) and zones outside the floodplains (NFZ: no-flood zone). The boundaries of each zone have been determined based on official flood risk maps (scale of 1:10,000) produced by Environment Canada and the Ministère de l'Environnement du Québec [35] and municipal land-development plans [36]. The soil samples were collected along the transects from the riverbank and extend past the floodplain's outer boundaries. The soil samples were collected directly inside the soil profile trench or with an Eijkelkamp hand auger at predetermined depths for a total depth of 1 m. Additional samples were collected on the soil surface (0–20 cm) at each site, for a total of 529 soil samples. Litter was also measured with a metric metal ruler, including a description of the dominant plant species and data on surface drainage, presence/absence of groundwater, and microtopography. There was a total of 246 sites in the different study areas, including 135 sites in the FFZ, 48 in the MFZ, and 63 in the NFZ. For the surface soils alone (0–20 cm), there were 181 soil samples in the FFZ, 67 in the MFZ, and 89 in the NFZ. Lastly, 192 additional soil samples were collected at different depths of the soil profile (20–40, 40–60, 60–80, and 80–100 cm), including 113 in the FFZ, 39 in the MFZ, and 39 in the NFZ. Measurements were made and soil samples collected from 2004 to 2016 (summer and fall). All the geographical coordinates for the sampling sites were recorded on digital maps using GPS points (UTM coordinates) measured directly in the field. All the geographical coordinates for the sampling sites were recorded on digital maps using GPS points (UTM coordinates) measured directly in the field.

2.3. Soil Sample Analysis

All the soil samples were taken to determine the SOC content in each soil layer (e.g., 0–20, 40–60, or 80–100 cm). Additional soil samples (0–20 cm layer) were collected to determine inter-site variability. Other analyses were done on the same samples, including acidity, particle size analysis (texture), total nitrogen, bulk density, and Al and Fe (pyro.%) concentrations, using the methods indicated in the Canadian System of Soil Classification manual [37]. Al + Fe concentrations are an indicator of soil development. For instance, concentrations greater than 0.4% (Al + Fe pyro.) for soils with a sandy matrix allows the soils to be categorized as podzols, which is an indication of their pedogenetic development [37,38]. The soils were air-dried, sieved through a copper steel screen (<2 mm), and weighed using an electronic scale in the laboratory. To determine particle size, the samples were analyzed using a laser particle sizer (Fritsch "Analysette 22" MicroTec Plus), based on an interval class ranging from 0.08 to 2000 microns. Only fragments less than 2 mm in size were analyzed with the laser device, while coarser fragments (>2 mm) were excluded from the grain size analysis. The texture classes are those found in the Canadian System of Soil Classification [38] and correspond to those of the Food and Agriculture Organization-Soil Taxonomy international system (FAO-USDA) [39].

Soil bulk density was determined at all the sites (flood and no-flood zones) in the 0–20 cm layer. The SOC content was determined using the method developed by Yeomans and Bremner [40], the main steps of which are as follows: (1) the samples are placed in a digestion tube to which 5 mL of potassium dichromate ($K_2Cr_2O_7$) is added for 30 min. The digestion tube is then heated at 170 °C for 30 min; (2) the sample is cooled and solutions of anthranilic acid (0.3 mL) and sodium carbonate are added; (3) this is followed by titration with a solution of ammonium ferrous sulfate (0.05 mol·L^{-1}). The soil nitrogen was determined with the Kjeldahl method [41], and the Carter and Gregorich method [42] was used to determine soil acidity, with a $CaCl_2$ solution (0.01 M) at a ratio of 1:2. Soil acidity was measured using an electronic pH meter equipped with a glass electrode. Lastly, Fe and Al (%) concentrations were determined using the method by Ross and Wang [43] with a 0.1 M solution of sodium pyrophosphate.

To evaluate C stocks in soil samples, we used the method by Tremblay et al. [44], which has been applied to forest stands. The equation is:

$$Q = C \times Bh \times T\,h \quad (1)$$

where, Q = Quantity of organic C in the horizon (t·ha^{-1}); C = Concentration of organic C in the horizon (%); Bh = Bulk density of the horizon (g·cm^3); Th = Thickness of the horizon (20 cm), excluding coarse particles >2 mm.

2.4. Data Analysis

Different physical and chemical soil properties (e.g., particle size, bulk density, total organic carbon, total nitrogen) were compiled in Excel files and reformatted for the processing of statistical analyses. An analysis of variance (ANOVA) and the Tukey's HSD (honest significant difference) test were used to check the values of the resulting averages and the statistically significant thresholds (p-value) compared to different variables and groups that were analyzed based on the various flood recurrence zones (FFZ and MFZ) and the no-flood zone (NFZ). The Kruskal-Wallis non-parametric test was used for the litter thickness variable due to the high number of zero values in the database. Correlation analyses of the soil properties (0–20 cm layer) were also done with the Spearman test. A confidence interval of 95% (p = 0.05) was used for the statistical processing using *R* statistical software (version 3.1.3, University of Auckland, Auckland, New Zealand,).

3. Results

3.1. SOC Content

Table 1 provides basic statistics on the SOC content on the soil surface (0–20 cm) for the various areas under study. The soil samples were obtained from floodplains subject to frequent flooding (recurrence of 0–20 years). According to the study areas, the average %SOC values range from 1.27% to 2.93%, with minimum and maximum values of 0.17% and 5.66%. The highest %SOC values come from the Coaticook (5.66%), Massawippi (5.13%), and Windsor (5.15%) areas, while the lowest level was measured at the Richmond area (0.17%). According to the coefficient of variation (CV%) obtained through the standard deviation and mean ratio, the data spread is relatively comparable (Table 1), except for two areas (Eaton and Sherbrooke) that are under-represented in the number of soil samples (<15). Lastly, with respect to the coefficient of skewness and of kurtosis, which provide measurements on distribution and skewness of the data based on the normal curve, the %SOC values that were obtained can be seen to have a normal distribution for the Drummondville, Richmond, and Windsor areas. This can be explained in part by the higher number of soil samples collected at these different sites (total of 107).

Table 1. Percentages of soil organic carbon (SOC) in mineral soil of the surface layer (0–20 cm) in frequent flood zones (FFZ) for different areas (southern Québec, Canada).

Sector	Minimum	Maximum	Mean	Standard Deviation	CV (%)	Coefficient of Skewness	Coefficient of Kurtosis
Coaticook	0.70	5.66	2.93	1.43	0.49	0.10	−1.10
Drummondville	0.81	4.80	2.00	0.97	0.48	2.09	5.75
Eaton	0.92	1.57	1.27	0.33	0.26	−0.67	-
Massawippi	0.53	5.13	2.58	1.16	0.45	0.34	−0.45
Richmond	0.17	4.60	1.71	0.76	0.44	1.13	3.65
Sherbrooke	1.51	2.16	1.80	0.33	0.18	0.91	-
Windsor	0.63	5.15	2.05	1.01	0.49	1.35	1.73

3.2. Soil Properties in Inundated and Non-Inundated Zones

Significant differences are noted between the soils in the flood zones and no-flood zones with respect to certain soil properties (e.g., acidity, particle size, bulk density, cation exchange capacity (CEC), Al + Fe concentrations). Regarding soil acidity, the pH values are considerably lower in the non-alluvial soils (3.97 ± 0.74) compared to the flood zones, i.e., 5.01 ± 0.67 (FFZ) and 4.58 ± 0.98 (MFZ), respectively. The pH results show that the NFZ soils are generally more acidic than the floodplain soils (FFZ) (Table 2). These differences may be attributable to many factors, including the origin of the parental material and the presence and composition of litter that can affect soil acidity. During mineralization and humification, the degradation of organic matter results in the formation of different acidifying organic compounds, in addition to releasing various elements such as free ions [45]. The release of acidifying compounds (e.g., fulvic and humic acids) necessarily causes an acidification of the soils in the surface layers, which can also favor the leaching of less soluble elements such as Al and Fe [46]. The values for soil particle size (texture) are similar among all the soils, with comparable proportions for sand and silt (Table 2). The dominant textures are loam, loamy sand, and sandy loam. The average values for sand and silt are, respectively, 52.79% and 41.82% (FFZ), 44.96% and 52.65% (MFZ), and 51.89% and 45.77% (NFZ) (Table 2). The proportion of clay is not over-represented for all the soils analyzed and rarely exceeds 5% (average). The texture of the mineral soils in the flood zones is mainly silt loam or silt, while sandy loam is the dominant texture in NFZ soils. These soils can also contain gravel or pebbles observed in the uppermost part or at the base of the soil profiles. The proportion of coarse elements (>2 mm) in the soil samples was measured at less than 5% (the weight was not measured for the coarse fraction) and the profiles containing coarse elements represent less than 4% of the studied sites. These coarse matrices are due to the nature of the parental material, which originates either from reworked till or heterogeneous glacial deposits. However, glaciolacustrine deposits and ancient fluvial deposits are mainly found outside the flood plains [32,33]. Bulk density shows comparable values among the various zones, which partly reflects the dominant textures of the soils that were analyzed, including the sandy and silty proportions which are relatively comparable between the sites. The average densities obtained for each zone were 0.96 ± 0.25, 0.92 ± 0.36, and 1.12 ± 0.18 $g \cdot cm^{-3}$, respectively. However, the results of the statistical tests revealed significant differences between the FFZ and NFZ and MFZ and NFZ, but not any significant difference between FFZ and MFZ (Table 3). The cation exchange capacity (CEC) shows equivalent values for the soils in the flood zones (8.94 ± 5.43 and 7.99 ± 6.28 $cmol \cdot kg^{-1}$), but a slightly lower value for non-alluvial soils (4.02 ± 5.13 $cmol \cdot kg^{-1}$). Regarding Al and Fe concentrations, notable differences are found in soils in the floodplain zones and in the no-flood zones. The Tukey test revealed significance differences between all zones. It should be noted that Al + Fe (pyro.%) concentrations higher than 0.6% are an indication of soil development in the Canadian System of Soil Classification [38]. The NFZ soils have higher concentrations than in the two flood zones, with an average value of 0.96 ± 0.55% compared to 0.41 ± 0.27% (FFZ) and 0.66 ± 0.40% (MFZ). As these soils are not subjected to flooding, the soil-forming process occurs under more stable conditions, which allows these elements to be transferred by leaching from the surface (e.g., Ah or eluvial horizons) to the illuvial horizons (e.g., Bm, Bfj, or Bf horizons). As these soils are more acidic (3.97 ± 0.74 on average), the mobilization and transfer of Al and Fe ions is made all the more easier with an acidity level below 4 or 4.5 [45–48]. The mobilization of these metal ions toward the deeper layers (e.g., 20–60 cm) is easily detected through the more marked horizonation in the soil profile. The Tukey test confirmed that Al + Fe% values are significantly different between the soils of the three zones (Table 3).

Table 2. Properties of mineral soil surface layer (0–20 cm) in the different flood zones (FFZ, MFZ) and no-flood zones (NFZ) in southern Québec (Canada).

Material Parental	Frequent Flood Zone (FFZ)	Moderate Flood Zone (MFZ)	No-Flood Zone (NFZ) (n = 33)
	Recent Fluvial Deposits	Recent Fluvial Deposits	Glaciolacustrine, Ancient Fluvial Deposits, Remaining Tills
Particle size (%)			
Clay	3.48 ± 3.59	2.39 ± 1.68	2.34 ± 3.57
Sand	52.79 ± 15.23	44.96 ± 14.88	51.89 ± 15.89
Silt	41.82 ± 15.06	52.65 ± 13.89	45.77 ± 14.23
Bulk density ($g \cdot cm^{-3}$)	0.96 ± 0.25	0.92 ± 0.36	1.12 ± 0.18
pH ($CaCl_2$)	5.01 ± 0.67	4.58 ± 0.98	3.97 ± 0.74
Soil organic carbon (%)	2.29 ± 1.64	3.14 ± 1.39	3.83 ± 2.22
Total soil nitrogen (%)	0.18 ± 0.09	0.23 ± 0.09	0.26 ± 0.17
C/N ratio	13.75 ± 3.58	13.56 ± 2.59	15.92 ± 4.14
C stock ($t \cdot ha^{-1}$)	38.22 ± 10.40	40.27 ± 20.25	79.75 ± 29.47
CEC ($cmol \cdot kg^{-1}$)	8.94 ± 5.43	7.99 ± 6.28	4.02 ± 5.13
Al + Fe (pyro.%)	0.41 ± 0.27	0.66 ± 0.40	0.96 ± 0.55
Litter thickness (cm)	1.09 ± 1.33	2.38 ± 2.35	3.70 ± 2.64

Fieldwork period 2002–2016. The values of soil samples are average with (±) standard deviation (n = 341). CEC, cation exchange capacity.

Table 3. Results of Tukey HSD (honest significant difference) test used for the comparison between soil surface (0–20 cm) for the three zones (FFZ, MFZ, and NFZ).

Comparison Between the Three Zones	Average [a]			p-Value [b]		
Soil Surface (0–20 cm) and Litter	FFZ	MFZ	NFZ	FFZ MFZ	NFZ FFZ	MFZ NFZ
pH	5.01	4.58	3.97	0.0001 **	0.0000 **	0.0000 **
%SOC	2.29	3.14	3.83	0.0000 **	0.0000 **	0.1928 *
%TN	0.18	0.23	0.26	0.0001 **	0.0000 **	0.9916 *
C/N ratio	13.75	13.56	15.92	0.9210 *	0.0000 **	0.0000 **
%Al + Fe	0.41	0.66	0.96	0.0231 **	0.0000 **	0.0327 **
Bulk density ($g \cdot cm^{-3}$)	0.96	0.92	1.12	0.1854 *	0.0007 **	0.0001 **
C stock ($t \cdot ha^{-1}$)	38.22	40.27	79.75	0.0057 **	0.0001 **	0.5548 *
Litter thickness (cm)	1.09	2.38	3.70	0.0001 **	0.0000 **	0.0305 **

[a] FFZ: Frequent flood zone; MFZ: Moderate flood zone; NFZ: No-flood zone; [b] Kruskal-Wallis test is used for this variable; * No statistical difference between groups ($p > 0.05$); ** Statistical difference between the three zone ($p < 0.05$). TSN, total soil nitrogen.

3.3. SOC, TN, and C/N Ratio

In comparing the three zones, the lowest concentrations of organic C come from the soils in the frequent-flood zones (FFZ), with mean values of 2.29 ± 1.64 (%SOC) and 38.22 ± 10.40 (C stock in t·ha^{-1}), whereas the highest concentrations are especially found in the non-alluvial soils (NFZ), with values of 3.83 ± 2.22% and 79.75 ± 29.47 t·ha^{-1} (Table 2). For the soils in the moderate-flood zones (recurrence of 20–100 years), the SOC and C stock values are slightly higher than for the FFZ soils: 3.14 ± 1.39% and 40.27 ± 20.25 t·ha^{-1}, respectively. In terms of percentages, the C stocks in the non-alluvial soils (NFZ) represent a volume that is more than 50% greater than the soils in the frequent-flood zones (FFZ). Note that C stocks are calculated from SOC concentrations and bulk density (BD) values for the 0–20-cm layer (see equation). The statistical Tukey test (Table 3) confirmed that %SOC and C stock values differ significantly between the FFZ zone and the other two zones (MFZ and NFZ). The same trend can be observed for the soil total nitrogen (%TN) values, with a lower average value in the FFZ of 0.18 ± 0.09%, compared to 0.23 ± 0.09% (MFZ) and 0.26 ± 0.17% (NFZ). The Tukey test showed that %TN is significantly different for the soils in the frequent-flood zone than for other two zones (Table 3). The C/N ratio for the data obtained does not show a statistical difference among the different flood zones. The average values are 13.75 ± 3.58 (FFZ), 13.56 ± 2.59 (MFZ), and 15.92 ± 4.14 (NFZ), respectively. The values obtained for BD were found to be statistically significant between FFZ and NFZ, and MFZ and NFZ. Lastly, the different soil textures appear to have a greater impact on soil C stocks (Figure 2). Note, for example, that MFZ and NFZ soils consisting of sandy loam or loamy sand have slightly higher C stocks (Figure 2). However, the C stocks in the FFZ soils are virtually similar, regardless of soil texture. The statistical test confirmed a significant difference (%SOC and C stocks) between the soils of the three zones (Table 3).

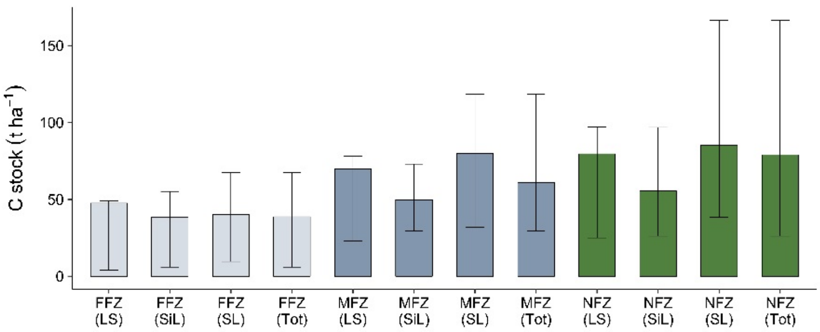

Figure 2. C stocks (t·ha^{-1}) in the mineral soil of the surface layer (0–20 cm) for each flood zone (interval of 0–10 years and 20–100 years) and no-flood zone (NFZ). Letters in parentheses represent different textural matrices (SiL: Silt loam; SL: Sandy loam; LS: Loamy sand; Tot: Total soil samples). (This figure includes all the sites).

3.4. Variability in Soil Profiles

Figure 3 shows different properties of the soil profiles for the three zones. With respect to the vertical distribution of %SOC, concentrations are generally lower in deeper layers than on the soil surface (Figure 3). The mean values obtained between the surface layer (0–20 cm) and deeper layer (80–100 cm) in each zone are 2.39–0.68% (FFZ), 3.30–0.63% (MFZ), and 3.80–0.38% (FFZ), respectively. The vertical distribution of %TN in the soil profiles is similar to that observed for SOC, namely, higher concentrations in the surface horizon than in the deeper horizons. The average values of the upper and lower layers are 0.18–0.07% (FFZ), 0.23–0.06% (MFZ), and 0.26–0.04% (FFZ). It can be noted, however, that %TN is slightly higher for FFZ soils in the deeper layers (between 40–100 cm), but the differences remain slight.

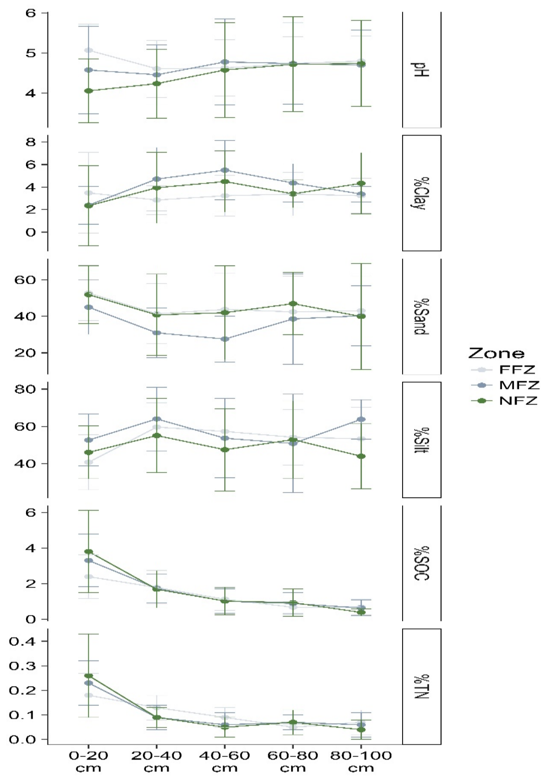

Figure 3. Graph of soil profiles (0–100 cm deep) with concentrations of SOC (%), TN (%), Clay (%), Sand (%), Silt (%), and pH values for the three study areas (FFZ, MFZ, and NFZ).

With respect to soil acidity, the mean pH values at the soil surface are lower for the non-alluvial soils (4.06 ± 0.79) compared to the soils in the frequent-flood zones (5.07 ± 0.65). The pH values at the base of the soil profiles are similar between the three zones, with averages between 4.7 and 4.8. This suggests that the presence of litter has a direct influence on the acidity of the surface soil. The decomposition of dead material and modified organic matter results in the formation of various components, including fulvic and humid acids, which contribute to soil acidification. Lastly, for the texture data, the proportions of silt and sand are comparable between the FFZ and NFZ soils, whereas the proportions of silt are slightly higher for the MFZ soils, while the proportion is slightly lower on the surface of FFZ soils. The proportion of clay is comparable for all the soil profiles, with average values below 5.5%.

3.5. Litter in Inundated and Non-Inundated Zones

The soils in the frequent flood zones are characterized by less or no litter (>50% of sites), while litter is found at all the MFZ and NFZ sites (Table 2). The average litter thickness at all the sites is 1.09 ± 1.33 cm (FFZ), 2.38 ± 2.35 cm (MFZ), and 3.70 ± 2.64 cm (NFZ). In the frequent-flood zones, the soil surfaces are most often bare, with herbaceous plants with a dense root system (e.g., *Matteuccia struthiopteris* (L.) Tod. and *Laportea Canadensis* (L.) Weddell) being most resistant to successive flooding. The NFZ soils are usually completely covered with litter, while the organic cover of the MFZ soils can be discontinuous.

Differences in the litter thicknesses at each of the three zones were confirmed by statistical analyses (Kruskal-Wallis test), with significant differences between the FFZ and MFZ soils and the FFZ and NFZ soils (Table 3). Lastly, the correlation test (Spearman coefficient) performed between the %SOC values and the litter thickness (cm) confirmed a moderate to strong link between these two variables (Figure 4), and the relationship is more correlated for FFZ (r = 0.478), suggesting that the absence of litter indicates a low level of SOC in the subsurface soil (0–20 cm).

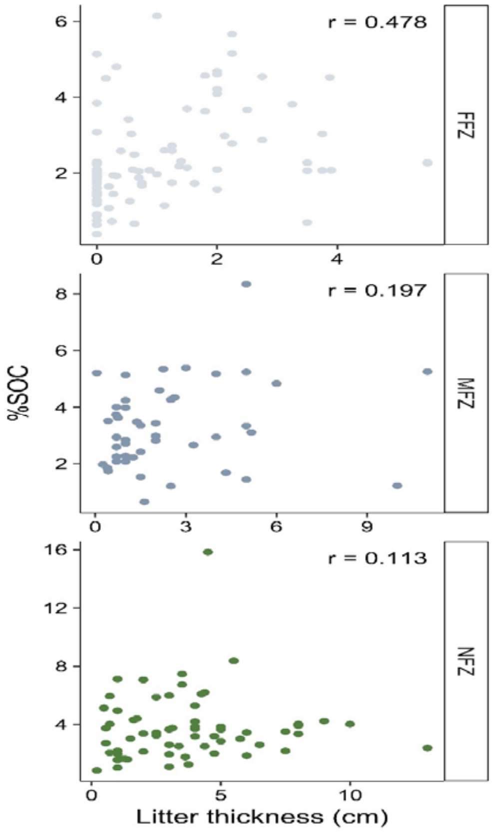

Figure 4. Relationships between the SOC (%) in surface soils (0–20 cm deep) and litter thickness (cm) using Spearman's correlation, including the three zones (FFZ, MFZ, and NFZ). All the data were examined at a significance level of $p = 0.05$ (95%).

4. Discussion

4.1. Variability in SOC and N

A large variability is noted in the values obtained for the soils in the different zones with respect to organic (%SOC) and total nitrogen compounds (%TN). The results obtained for SOC and N concentrations in the surface layers (0–20 cm) confirm that the input of organic matter is minimal in the frequent flood zones. FFZ soils often do not have any thick litter, and are characterized by numerous bare surfaces resulting from successive floods. This considerably affects the input of organic matter to the soil, which results in reduced C and N content, and hinders the accumulation and storage of C in the soil. The distribution pattern of SOC content in FFZ soil profiles in fact does not show any marked difference between the surface and the base of the profile (0–100 cm), compared with the MFZ and NFZ soils (Figure 3). This results in SOC depletion due to the insufficient input of organic matter, a large portion of which comes from the litter. Note that half of the FFZ soils that were examined are stripped of litter due to successive floods. For the non-alluvial soils, a different distribution in SOC is noted that is most often characterized by higher concentrations in the surface layers (Figure 3). This type of distribution is similar to the soils in wooded areas in temperate regions which are characterized by thick litter that forms from an accumulation of dead leaves at the end of fall [49–52]. Given that the main source of SOC is litter (e.g., dead leaves, twigs, stems) or the decomposition of fine rootlets, higher concentrations will naturally occur in the surface layers [53–55]. This ensures a constant input of SOC and allows it to be stored, in particular in a form that is not very soluble or humified [55,56]. However, the storage of C in the deeper layers of the profile (>60 cm) constitutes a negligible input.

The studies conducted in fluvial environments show certain divergent results as to the effects of floods on the accumulation of organic matter and SOC concentrations. For instance, a certain number of studies [14,25,57] show that there is no significant difference between SOC concentrations in floodplain soils and in non-alluvial soils (e.g., upslope stands). For instance, the study of Hazlett et al. [57] indicated that "Forest floor layers were deeper and stored more C and N in riparian forest stands in comparison to upslope stands". "Riparian forests did not differ from upslope stands in terms of total aboveground overstory C storage . . . .". "In contrast, mineral soil in upslope stands had greater C and N storage than mineral soil horizons within the riparian forests." ([57], p. 56). The study by Bayley and Guimond [25] indicated, however, that "Riverine floodwater pulses provide water, nutrients, and sediments to floodplain wetlands, but floods also act as a natural disturbance by removing biomass and scouring sediments, . . . "([25], p. 1243). Lastly, the study by Cierjacks et al. [18] showed that "The concentration of organic C in subsoil horizons increased significantly with the distance to the main channel." ([18], p. 1), although some soils close to the river may contain high SOC concentrations. In other words, the impact of flooding on soils is complex and difficult to predict [25], and the conditions specific to each site must be taken into account.

4.2. Litter

Floodplain soils subjected to successive flooding cannot readily accumulate organic matter, and surfaces are most often totally stripped of litter. More than 50% of the FFZ sites that were examined were stripped of litter and, when litter was present, it was most often less than 2 cm thick (average of 1.09 $\pm$ 1.33 cm), forming discontinuous covers. In the zones not affected by flooding (NFZ), litter can accumulate over the years, thus ensuring to some extent a permanent source of organic matter [58]. The degradation of this organic input (mineralization and humification) and its progressive incorporation in the soil favor the transfer of various nutrients such as SOC and N in the soil profile. Figure 5 shows a diagram of the processes observed in the various zones that were studied, including those affected by successive flooding (FFZ). During flood events, the river current can easily dislodge organic debris from the soil surface as well as fine layers of sediment (erosion phase). Organic matter that accumulates during the growing season and in the fall (e.g., dead leaves, needles) can be dislodged, leaving behind only bare surfaces. Only trees, shrubs, and deeply rooted plants (e.g., *Matteuccia struthiopteris*) are capable of withstanding the strength of the current. If the current is especially strong, not only can organic debris on the ground be dislodged and carried off further downstream, but yearly plants or tree seedlings also run the risk of being pulled up, thus considerably hindering vegetation renewal and forest regeneration. At flood recession (deposition phase), sedimentary deposits (generally silt or very fine sand) can be observed along riverbanks and may form continuous covers over terrace benches. These accumulations can reach 4–5 cm or more and can bury young plant and tree seedlings and thus decrease their chances of survival. These phases of erosion and deposition also occur in the moderate-flood zones (recurrence of 20–100 years), but because of the strength of the current and especially less-frequent flooding, the combined effects of these fluvial processes (erosion versus deposition) are much less intense. More pronounced soil development can also be noted, which results in the formation of a thin organo-mineral layer (Ah horizon). For soils in the no-flood zones, the processes that take place are similar to forest soils, which are characterized by abundant litter, soil fertility through various nutrients (C and N for instance), and more marked horizonation of the soil profile. Thicker (>5 cm) organo-mineral (Ah) horizons are found that are enriched with humified particles, along with illuvial horizons (Bm, Bfj, or Bf horizons) that indicate active soil-forming processes, including the accumulation of Al and Fe sesquioxides. Flood frequency thus has a direct impact on soil development, especially for alluvial soils subjected to successive flooding with profiles that can be qualified as "rejuvenation profiles" [26,27].

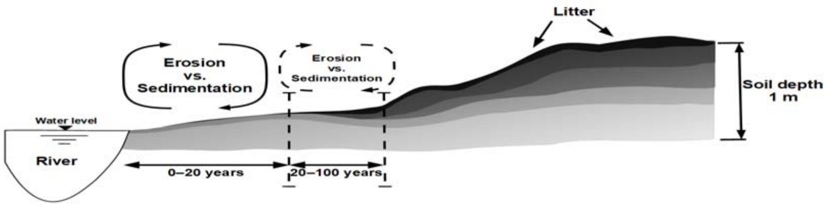

Figure 5. Schematic graph illustrating the main soil development observed in the different zones. Fluvial erosion and sedimentation processes have affected soil development and may alter soil quality and fertility. The accumulation of litter is difficult in the frequent-flood zone (FFZ: recurrence of 0–20 years) due to successive flooding, which prevents a large input of organic matter that could have a direct effect on SOC and N contents. Furthermore, sedimentation causes soil rejuvenation, which results in little differentiation among soil profile horizons. In the no-flood zones (NFZ), litter accumulation is much more constant and soil development occurs under more stable conditions, which results in more pronounced soil horizons. In the moderate flood zone (MFZ: recurrence of 20–100 years), conditions are similar to FFZ, but with less detrimental effects on the soil-forming process. Erosion and sedimentation processes in the MFZ are also less marked than for the FFZ.

4.3. Flood Events

Recent studies on flood frequency in the south-central Québec study area [28,29,59,60] show an increase in floods over the last three decades, with somewhat more pronounced peaks in the last few years (Figure 6). This increase in flood events also results in an increase in summer and fall floods, although spring floods are more numerous [58–60]. For example, between 1960 and 2010, over 60 flood events were recorded in south-central Québec catchments, with close to 50% occurring in the spring [58]. Because of these new hydrologic conditions resulting from increased flooding, it can be easily assumed that they will deeply alter floodplain soils, including an alteration of soil-forming processes and soil depletion (in terms of C and N, for instance), induced by the loss of ground litter resulting from successive floods [26,27,58]. Furthermore, successive floods that progressively modify the fluvial environment could cause major alterations to riparian forests, namely in relation to the regeneration capacity of the tree stratum and the maintenance of current forest stands [61]. These wooded areas may experience a progressive decline and be replaced with a new group of shrub or tree species better suited to the new hydrologic conditions. Species that are less demanding in terms of soil nutrients may also benefit from the new conditions.

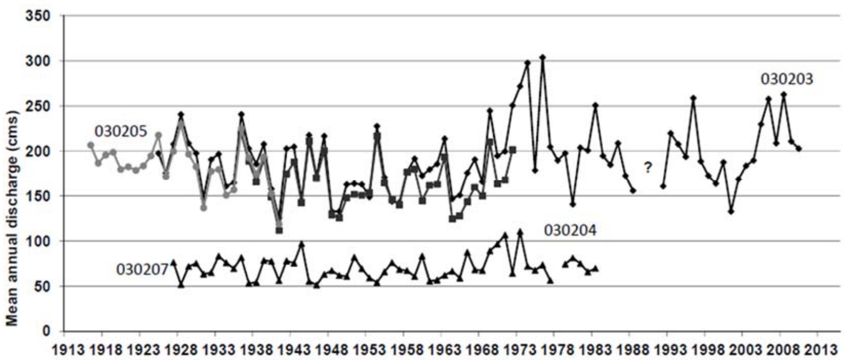

Figure 6. Mean annual discharges for 1913–2013 for the rivers located in study area floods [27–29]. Hydrological data are based on flow records from different gauging stations [30]. (Note: Several gauging stations are permanently closed, making it difficult to establish long-term hydrological time series.)

5. Conclusions

The soil data for this research is based on large number of sites distributed across different flood zones and no-flood zones in riparian woodlands. The results show marked differences in the SOC and N contents based on the different zones that were studied (FFZ, MFZ, and NFZ). It was noted that the %SOC and %TN values and C stocks are significantly lower in soils in frequent flood zones (FFZ). The %SOC values are higher in soils in the no-flood zones (NFZ). The soils in the moderate flood zones (MFZ) have some values that approximate the no-flooded soils. The low %SOC and %TN values measured in FFZ soils are largely due to the absence or virtual absence of litter that prevents a constant inflow of organic carbon. Over time, this results in the depletion of SOC in the soil along with reduced soil quality and fertility. If current hydrological conditions persist (e.g., more frequent floods), a more pronounced impoverishment of soils affected by successive floods can be expected. Finally, these measures of SOC can form a baseline for other studies and can be used for monitoring and impact assessment in relation to climate change.

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Abbreviations

FFZ	Frequent flood zone
MFZ	Moderate flood zone
NFZ	No-flood zone
SOC	Soil organic carbon
GPS	Global positioning system
UTM	Universal transverse Mercator

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