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Spatial distribution of organic carbon and nitrogen in soils related to flood recurrence intervals and land use changes in Southern Québec, Canada

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Several hydromorphological and soil factors may be the cause of variations in the total organic carbon (TOC%) and total nitrogen (TN%) content of riparian soils. Despite the importance of these two essential components in soil-forming processes, few studies have focused on the variability of carbon and nitrogen content for soils subjected to frequent flooding. Successive floods may in fact result in soil depletion. Measurements of TOC% and TN% content as well as of other physico-chemical soil properties (e.g. litter thickness, texture, pH, Fe and Al concentrations, C/N ratio, bulk density, colour) were performed in various flood zones (recurrence intervals of 0-20 and 20-100 years) and in no-flood zones (outside of floodplains). To do so, soil samples were systematically collected along transects perpendicular to the riverbank which cross through the various flood zones. The results show that TOC% and TN% content varies significantly from one zone to another. The concentrations of these two components are significantly lower in the flood zone with a recurrence interval of 0-20 years (29% ±0.80 TOC and 0.17% ±0.05 TN) compared to the other two zones, name 3.45% ±1.56 TOC and 0.26% ±0.10 TN (recurrence interval of 20-100 years), and 3.52% ±1.57 TOC and 0.27% ±0.11 TN (no-flood zone). There is often no soil biomass (litter) in flood zones with a flood recurrence interval of 0-20 years (72% of sites without litter), whereas litter is almost always present in the flood zone with a recurrence interval of 20-100 years and in the no-flood zone, with average thicknesses of 2.84 and 3.65 cm, respectively. The absence or virtual absence of litter in the frequent-flood zones progressively results in soil depletion in terms of CO and N, which over time could adversely affect forest stand regeneration and deeply alter current river ecosystems.

Key words: Alluvial soils, total organic carbon (TOC), total nitrogen (TN), soil biomass, floodplain, flood, recurrence intervals.

INTRODUCTION

Organic carbon and nitrogen are important indicators of soil fertility and quality. These two components also have a direct impact on soil biochemistry, in addition to contributing to the vitality of plants and forest stands (Myster, 2015; Yang et al., 2016). The organic carbon and nitrogen content in soil varies temporally and spatially based on numerous soil, hydroclimatic and morphological factors as well as soil use (Bedison et al., 2013; Häring et al., 2013). Soil biomass (litter), the main source of organic matter, is also a key element for measuring soil fertility and nutrient content. It is also known that the distribution of organic carbon and nitrogen can vary based on the depth of the soil profile (Don et al., 2007; Schilling et al., 2009) and that these two components are especially concentrated in surface horizons, frequently referred to as the “rhizosphere”, the first 20 cm of soil profile and that this percentage decreases with soil depth (0-100 cm). It is also known that organic carbon and nitrogen concentrations can vary based on soil use (Wiesmeier et al., 2013). Farmed soils, for instance, can contain fewer nutrients than grassland and forest soils. Mechanical tillage of the soil and especially small amounts of crop residue may result in progressive soil depletion.

Lastly, certain physical soil properties such as bulk density (Don et al., 2007), texture (Bedison et al., 2013), water saturation and leaching (Wiesmeier et al., 2013) can also affect the organic carbon and nitrogen contents in soils.

In riparian areas, soil-forming processes are significantly affected by river dynamics (Bayley and Guimond, 2011; Myster, 2015). For instance, the soil organic carbon and nitrogen content can vary considerably based on river flows and the flood regime. Cierjacks et al. (2010) have shown that soil organic content in riparian areas increases further away from the main channel. Also, the phenomenon of vertical aggradation (that is, accumulation of flood sediment) maintains the soil in an immature state and inhibits the mineralization and humification processes essential to biogeochemical cycles (Bayley and Guimond, 2011; Gervais-Beaulac et al., 2013). It was also found that overly frequent floods contribute to leaching of the nutrients contained in the soil organic matter and that the stripping of surface litter progressively leads to soil depletion (Bayley and Guimond, 2011; Bedison et al., 2013; Gervais-Beaulac et al., 2013). Bedison et al. (2013) showed that about 70% of the forest sites that were studied in flood zones had no organic horizons and that the mineral matrix had low organic carbon and nitrogen contents. Although numerous studies have been done on the relationship between soil use and soil organic carbon and nitrogen (Don et al., 2007; Li et al., 2013; Schilling et al., 2009), there are few detailed studies on the effects of successive floods on CO and N content in alluvial soils (Bayley and Guimond, 2009; Bedison et al., 2013; Cierjacks et al., 2010). Recent works (Gervais-Beaulac et al., 2013, Saint-Laurent et al., 2014) have led to the determination that frequent floods can result in soil depletion and that organic carbon and nitrogen contents are significantly lower in frequent-flood zones than in areas prone to less flooding. This is attributed to the absence or virtual absence of litter that cannot accumulate on the surface of the soil due to very frequent floods (every 2 to 3 years, for instance), and the absence of litter prevents a major contribution of organic matter for the soil and progressively contributes to its depletion and lack of fertility. Given the importance of components such as organic carbon and nitrogen in soil biogeochemical processes, it seems critical to fully understand their distribution and variability in dynamic environments such as river systems. The main aim of this study is therefore to examine the spatial distribution of organic carbon and nitrogen for soils subjected to variable flood recurrence intervals (0-20 and 20-100 years). Sites located in no-flood zones but near riverbanks will also be studied for comparative purposes. Other key soil properties were analyzed, including pH, texture, bulk density and Fe and Al content. The study area covers a large floodplain (Richmond area) located on the left bank of the Saint-François River, a major watercourse in southern Québec (Canada). This large plain is characterized by periodic floods that affect the surface soil through erosion and sedimentation. At the same time, a diachronic analysis of the site using different series of aerial photographs (from 1945 to 2007) was done to track changes in soil use and to determine the possible effects of these changes on soil properties based on the various areas being studied.

MATERIALS AND METHODS

Study area

The study area is located in the Saint-François River catchment (Figure 1), which occupies roughly 10.228 km², 15% of which is found in the State of Vermont in the United States. This watershed is generally characterized by woodlands, which occupy about 65.7% of the area, followed by farmland (22.9%), with the remainder consisting of urban areas, watercourses, and wetlands (11.4%). The river landscape I characterized by ancient or recent alluvial sediments, while till deposits, glaciolacustrine sediments and rocky outcrops are mainly found along the riverbank and on higher ground (MEMR, 1989). 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 (Gervais-Beaulac, 2013). This region is known for having a humid continental climate with average annual temperatures of 5.6°C (1981-2010) and average annual precipitation of 1185 mm (Richmond Weather Station, 7026465; MDDELCC, 2015b).

The mean annual flow of the Saint-François River measured downstream of the study area is 190 m³/s (Chute-Hemming/Drummondville; Cogesaf, 2006), and the mean annual flow measured at the Sherbrooke Station (030208), located 40 k upstream of the study area, is 162 m³/s.

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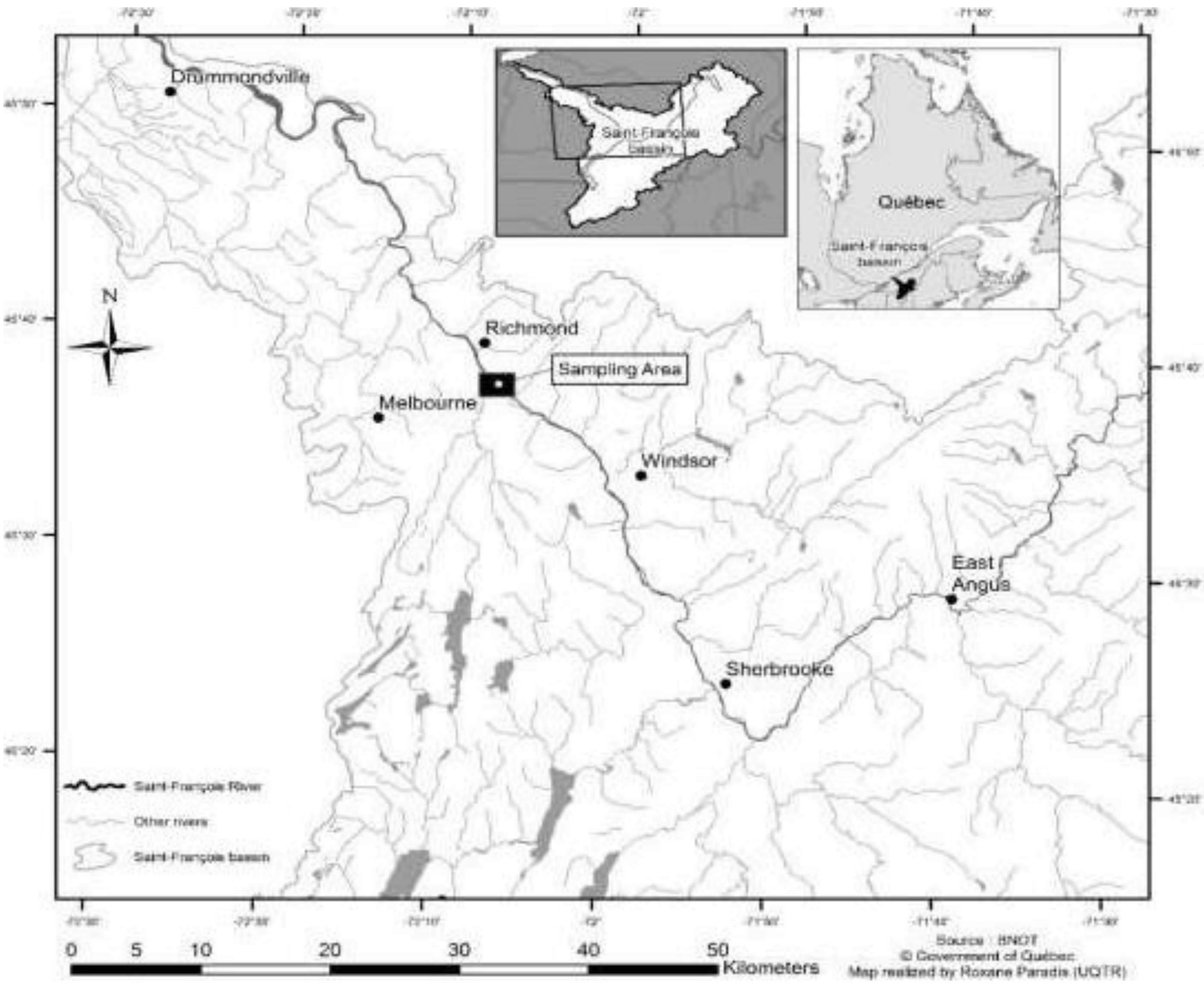

Figure 1. Location of sampling sites along the Saint-François River in the Richmond area (Southern Québec, Canada).

The river section between the towns of Drummondville and Sherbrooke is subject to frequent floods, especially since 1970s (Saint-Laurent et al., 2010). Richmond-Windsor is one of the municipalities that is most affected by the floods in the Saint-François River catchment, and it is estimated that over 55 floods (mainly in the spring) have occurred between 1900 and 2015 (Saint-Laurent et al., 2010).

In this area, the riparian forests and woodlands are most often found on the low terraces (1-2 m in height) and the tree stands are mainly characterized by red ash (*Fraxinus pennsylvanica* Marsh.), silver maple (*Acer saccharinum* L.), sugar maple (*Acer saccharum* L.) and balsam fir (*Abies balsamea* L.), while slopping terrain is characterized by hemlock (*Tsuga canadensis* L.), white pine (*Pinus strobus* L.), fir (*Abies balsamea* L.) and yellow birch (*Betula alleghaniensis* Britton) (Berthelot et al., 2014). Despite some diversity of forest stands in the frequently flood zone, there is less dense vegetation cover and especially a lack or thin layer of soil litter on the ground.

Sampling sites

The soil sampling sites were located along transects perpendicular to the riverbank within the floodplain that cuts across wooded areas. The layout of the transects inside the site took into account the site topography and the cartographic boundaries of the various flood recurrence zones determined with official flood risk maps (scale of 1:10 000) produced by Environment Canada and the Ministère de l'Environnement du Québec (EC-MENV, 1982). These boundaries consist of two flood-risk zones, including the zone with a flood recurrence interval of 0-20 years (FFZ: frequent flood zone) and the zone with a flood recurrence interval of 20-100 years (MFZ: moderate flood zone). The transects also extend beyond the flood zone boundaries, thus cutting across an area outside the floodplains (NFZ: No-flood zone). The soil samples were collected along the transects from the river bank and extend past the floodplain's outer boundaries. The samples were collected every 50m using an Eijkelkamp hand auger at predetermined depths

(0-20, 20-40, 40-60, 60-80 and 80-100 cm). Additional samples were collected on the soil surface (0-20 cm) every 25 m along the transects, for a total of 155 soil samples. Hence, there are 26 sites in the FFZ, 27 in the MFZ and 33 in the NFZ.

A characterization of the soil litter along with a description of the dominant plant species were noted at each sampling station, as well as measurements of the bulk density of the soil surface horizons (0-20 m), the microtopography, the presence/absence of groundwater, and the surface drainage based on the criteria outlined in the Canadian System of Soil Classification (CSSC, 1998) and the Manual on Soil.

Sampling and methods of analysis

The sampling period was from August to November 2014, and the position of the sampling points along the transects was determined using a GPS (Garmin 60CSx) after which the data were exported into mapping software (ArcGis® 10.2).

Physical and chemical analysis of soils

The soil samples were analyzed to characterize their main physical and chemical properties, mainly consisting of total organic carbon content (TOC%), total nitrogen (TN%), acidity, bulk density, Fe and Al (%), soil colors (Munsell Chart), and texture (CSSC, 1998). The samples were dried on aluminum plates (2-3 weeks) and then sieved through a wire sieve (<2 mm). For the analysis of bulk density (BD), the samples were weighed while wet and then when dry. The ratio between the weight of the sample (g) and the volume of the cylinder (ml) allowed the BD values to be determined for all the surface horizons that were sampled (0-20 cm). To determine the proportion of the particle sizes (sand, silt and clay), the samples were analyzed using a laser particle sizer (Fritsch "Analysette 22" MicroTec Plus), based on an interval class ranging from 0.08 to 2,000 microns. The texture classes are those found in the Canadian System of Soil Classification (CSSC, 1998) and roughly correspond to those of the FAO-USDA international system (FAO, 2015). The method used to measure the pH was taken from Soil Sampling and Methods of Analysis (Carter and Gregorich, 2008), which uses a $CaCl_2$ solution (0.01 M) at a ratio of 1:2. The total organic carbon content (TOC%) was determined using the method developed by Yeomans and Bremner (1988).

The Kjeldahl method was used for total nitrogen (Quikchem Method, 1996). Lastly, the iron and aluminum contents were measured using the method developed by Ross and Wang (1993) which uses sodium pyrophosphate as reagent. All the chemical analyses were carried out at the Université Laval soil laboratory (forestry, geography and geomatics Department).

Finally, to evaluate the C stocks in soils for different flood and no-flood zones, we used the method of Tremblay et al. (1995:5) which is comparable to that defined by Wiesmeier et al. (2015:3839). The equation is:

$$Q = C \times Bh \times Th \quad (1)$$

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

Diachronic analysis

To analyze the changes and developments in land use in the study area, a diachronic analysis was done using different series of available aerial photographs (1945, 1960, 1966, 1979, 1988, 1998 and 2007) (MRNF, 2012). These panchromatic photographs were scanned and georeferenced in order to analyze the main changes that occurred over the period involved (1945-2007). Orthophotographs were also used to determine the changes that may have occurred between 2007 and 2010 (MRNF, 2012).

The various land use surfaces (farmland versus woodlands) were traced in the form of polygons, and polygonal surfaces were calculated precisely to measure the respective surface areas. The ArcGis (version 10.2) and PCI Geomatica (Version 2013 SP2) software programs were used for the various steps involved in converting standard aerial photographs into scanned and georeferenced images. The years selected to represent the main changes in land use in the study area are 1945, 1966, 1998 and 2007.

Statistical analysis

The soil properties (total organic carbon content (TOC%), total nitrogen (TN%), pH, Fe and Al (%), textural classes and soil bulk density), and soil litter measurements were compiled in Excel files for the processing of statistical analyzes. An analysis of variance (ANOVA) and the Tukey's 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 no-flood zone (NFZ). Correlation analyses (Pearson test) of the various soil properties and litter thickness were also done. A confidence interval of 95% (p = 0.05) was used for the statistical processing using R statistical software (version 3.1.2).

RESULTS

Soil properties

Table 1 summarizes the main soil properties that were analyzed for the surface horizons (0-20 cm) based on the various study areas (FFZ, MFZ and NFZ). The average pH measured in the frequent flood zone (FFZ) was 4.94 ±0.74, compared to 4.70 ±1.33 for the moderate flood zone (MFZ) and 4.34 ±0.82 for the no-flood zone (NFZ). Bulk density (BD) was equivalent for all three zones. The average densities were 1.00, 0.99 and 1.10 g/cm³, respectively.

Regarding soil texture, the values are comparable among the two flood zones, in particular with respect to the proportions of sand and silt. The averages are respectively 44 and 46% for sand and 54 and 52% for silt. The average values obtained for the no-flood zones (NFZ) are 52% for sand and 46% for silt.

The proportion of clay, for its part, is relatively similar for the soils in all three zones, rarely exceeding 3% on average. Lastly, with respect to Fe and Al concentrations, notable differences are found in the floodplain zones and in the no-flood zones. The non-alluvial soils (NFZ) have higher concentrations than in the two other zones (FFZ and MFZ), which is likely due to more marked leaching of these elements (Fe and Al) toward the subsurface horizons (0-20 cm). The average concentrations range from 0.40 ±0.22% (FFZ), 0.67 ±0.40% (MFZ) and 0.98 ±0.57% (NFZ) for each respective zone. For the soils in

Table 1. Physical and chemical soil properties of surface layer (0-20 cm) in the different zones (FFZ, MFZ and NFZ) in Richmond sector (Southern Québec, Canada).

Frequent flood zone (FFZ) (*n* = 26)	pH ($CaCl_2$)	TOC (%)	TN (%)	C/N	Fe + Al (%)	Bulk density (g/cm^3)	C stock ($t.ha^{-1}$)	Clay (%)	Silt (%)	Sand (%)	Textural Class[a]	Colour[b] (Munsell Chart)
Mean	4.94	2.09	0.17	12.23	0.40	1.00	41.8	2	54	44	2	10YR 4/2
S.D.	(±0.74)	(±0.80)	(±0.05)	(±1.90)	(±0.22)	(±0.17)		(±2)	(±12)	(±13)	(±2)	10YR 5/2
Maximum	5.76	4.60	0.30	16.76	1.17	1.40	128.8	13	83	74	13	
Minimum	2.88	0.39	0.06	6.96	0.18	0.60	4.68	1	25	5	1	
Median	5.30	1.20	0.16	12.12	0.32	1.03	24.72	2	55	43	2	
Moderate flood zone (MFZ) (*n* = 27)												
Mean	4.70	3.45	0.26	12.88	0.67	0.99	68.31	2	52	45	2	10YR 4/2
S.D.	(±1.33)	(±1.56)	(±0.10)	(±2.79)	(±0.40)	(±0.25)		(± 2)	(±13)	(±14)	(± 2)	2.5Y 5/3
Maximum	7.19	8.34	0.59	20.33	1.30	1.57	261.88	12	75	73	12	
Minimum	2.88	1.21	0.14	7.81	0.10	0.63	15.25	1	26	13	1	
Median	4.16	2.97	0.26	12.69	0.64	0.96	57.02	2	56	41	2	
No-flood zone (NFZ) (*n* = 33)												
Mean	4.34	3.52	0.27	13.25	0.98	1.10	77.44	2	46	52	2	10YR 4/2
S.D.	(±0.82)	(±1.57)	(±0.11)	(±2.62)	(±0.57)	(±0.20)		(±2)	(±11)	(±13)	(±2)	10YR 3/2
Maximum	6.98	7.11	0.59	19.37	2.20	1.54	218.98	12	80	70	12	
Minimum	3.08	1.03	0.07	8.84	0.07	0.84	17.30	1	28	8	1	
Median	4.10	3.43	0.24	13.24	0.86	1.08	57.62	2	44	54	2	

[a]Textural classes (CSSC, 1998) and frequency (%). Dry colour.

the no-flood zone, the average concentrations are more than double compared to the values of alluvial soils (FFZ).

Soil biomass

Litter thickness varies significantly depending on the zone (Table 2). There is less litter in the FFZ zone than in the MFZ and NFZ zones. In general, FFZ soil is characterized by a small amount of litter (that is, no litter in 72% of the sites), while litter is present in all the sites for the MFZ and NFZ zones. The average litter thickness is 0.80 cm (FFZ), 2.84 cm (MFZ) and 3.65 cm (NFZ). Although the average litter thickness is relatively comparable among the MFZ and NFZ zones, some differences are found with respect to the composition and type of organic material (Table 2). There is generally less diversity of organic material for the MFZ versus the NFZ zone.

In addition, NFZ soils are usually completely covered with litter, while litter cover in MFZ zones can at times be discontinuous. The differences observed in litter thickness for the three study zones is confirmed by statistical analyses, which provide significant values between the FFZ and the MFZ zones and between the FFZ and NFZ zones (Table 3).

TOC% and TN% concentrations

Total organic carbon (TOC%) and total nitrogen (TN%) concentrations vary significantly based on the different zones under study.

Table 2. Soil biomass (litter) in the different zones (FFZ, MFZ and NFZ) in the study area (Richmond, Southern Québec).

Frequent flood zone (FFZ) (*n* = 26)	**Moderate flood zone (MFZ) (*n* = 27)**	**No-flood zone (NFZ) (*n* = 33)**
Characteristics and nature of organic debris at the top of soil surface (litter)		
Top of the soil surface: The vegetation cover is dominated by hardwood; low recovery of the canopy; dominant tree species: *Fraxinus pennsylvanica*, *Acer negundo* and *Acer saccharinum*; undergrowth dominated by ferns (*Matteucia Struthiopteris*), nettles (*Laportea canadensis*) and goldenrod (*Solidago canadensis*); litter are absent orrarely present and the ground surface is often stripped. (Photo A)	Top of the soil surface: The vegetation cover is dominated by hardwood and shrubs; low to moderate recovery of the canopy; dominant tree species: *Fraxinus nigra*, *Prunus serotina*; underground dominated by herbaceas (gramineae sp.); litter present in all sites; litter cover partially discontinuous; litter composed mainly by twigs, foams and some leaves; mull or moder plant litter dominated. The horizons in subsoil are more visibles in the profile. (Photo B)	Top of the soil surface: The vegetation cover is dominated by hardwood and conifers; moderate to high recovery of the canopy; dominant tree species: *Acer rubrum*, *Abies balsamea*; underground dominated by herbaceas and young trees; litter present in all sites; litter cover generally continuous; litter composed mainly by twigs, foams, leaves, herbaceous, mosses, and conifer needles. Mor or moder plant litter dominated. (Photo C)
	Average of litter thickness (cm)	
0.80 ± 1.66	**2.84 ± 2.80**	**3.65 ± 2.95**
		

The NFZ surface horizon contains 3.52 ±1.57% of organic carbon on average, while the average value is significantly lower for the FFZ, that is, 2.09 ±0.80%. The results of statistical tests (Tukey test) confirm that the values are significantly different between the FFZ zone and the other two zones (MFZ and NFZ). Values below 0.05 are obtained between the FFZ and MFZ zones and the FFZ and NFZ zones (Table 3).

The proportion of C stocks calculated in the three zones is comparable to the SOC concentrations measured in surface soil (0-20 cm) with average values of 41.8, 68.31 and 77.44 $t.ha^{-1}$, respectively.

The SOC values in the no-flood zone are almost double that estimated in the frequent flood soils (FFZ). With respect to total nitrogen (TN%), the lowest average concentrations were measured in the frequent flood zones (FFZ), with average value of 0.17±0.05%, compared to 0.27 ±0.11% for the NFZ. The statistical analysis shows that TN% concentrations in the no-flood zone differ significantly from the other values obtained for the floodplain soils (Table 3). Lastly, the C/N ratio for the data obtained between these two variables does not show a marked difference among the three zones. The average values are 12.23 ±1.90 (FFZ), 12.88±2.79 (MFZ) and 13.25±2.62 (NFZ), respectively.

Table 3. Tukey test in the comparison of mean values of TOC%, TN% and soil biomass between the different zones (FFZ, MFZ, NFZ) in Richmond area (Southern Québec).

Parameter	Group B	Group B	Group B
	FFZ and MFZ	FFZ and NFZ	MFZ and NFZ
Soil Biomass	0.012*	0.000*	0.445
TOC%	0.002*	0.000*	0.980
TN%	0.001*	0.000*	0.997

*Significant at P <0.05 (95%).

With respect to the vertical distribution of TOC% and TN% in the soil profile, concentrations are generally lower deeper in the soil than on the soil surface (Figure 2). Furthermore, variations in the average concentrations of organic carbon between the surface horizons (0-20 cm) and the deeper horizons (80-100 cm) are significantly more marked in the NFZ zone than the other two zones (FFZ and MFZ). The difference between the surface horizons (0-20 cm) and deeper horizons (80-100 cm) is 3.24% in soils of NFZ, 2.69% (MFZ) and 1.60% (FFZ) in alluvial soils respectively. The vertical distribution of TN% in the profiles is similar to that observed for organic carbon, namely, higher concentrations in the surface horizon than in the deeper horizons. The average values for the surface horizons are 0.17% (FFZ), 0.26% (MFZ) and 0.27% (NFZ). The average concentrations obtained at the base of the profile range from 0.02 to 0.05%, which are comparable for the three zones under study. A photography A (Table 2) shows an example of a soil profiles in FFZ which is characterized by a weak differentiation of horizons and no litter layer at the surface.

Table 4 shows the results of Pearson correlation tests obtained for organic carbon and nitrogen, as well as other soil properties measured on the soil surface (0-20 cm). The results show a highly significant correlation (r = 0.92) between TOC% and TN% concentrations. The presence of nitrogen in the soil is therefore closely linked to the presence of carbon, the main source of which is the breakdown of organic matter. Clay and silt are also positively correlated (r = 0.61). Lastly, there is a high negative correlation between sand and clay (r = -0.70) as well as between sand and silt (r = -0.99), which is easily explained by the contrasting differences between the respective proportions of each particle size.

Land-use changes

The diachronic analysis performed using the various series of aerial photographs (from 1945 to 2007) allowed researchers to monitor changes in land use in the study area as well as determine whether the changes that occurred during this period may have had a measurable impact on soil properties, including TOC% and NT% levels. The analysis revealed that the main changes consist of a densification and an extension of wooded areas at the expense of farmland, especially after the 1970s (Figures 3B and 3C). All the sampled sites were previously found on farmland (open fields), and this land progressively turned back into forest. In the areas next to Richmond and Windsor, especially along the riverbanks, this same phenomenon was also noted, which resulted in the farmland being abandoned in favour of wooded areas (Castonguay and Saint-Laurent, 2009).

If we more closely examine the changes that occurred between 1945 and 2007, the study area still constitutes an extensive agricultural area in 1945 (pasture land and forage fields), delimited by wooded areas (Figure 3A). Woody fringes can also be seen along the river banks. The photograph from 1966 shows an expansion and densification of wooded areas, in particular along the river banks and across the island (Figure 3B). Crop lands (especially forage plants) were abandoned in part in favour of forest areas (natural regeneration).

On the photograph from 1998, a large portion of the farmland is now covered with forest stands (Figure 3C). On the photograph from 2008, virtually the entire study area is under forest cover, with open or sparsely vegetated areas along the riverbank (Figure 3D).

These wooded areas were reconstituted naturally, except for a few patches resulting from planting activities. With the calculation of the surface areas measured on the georeferenced aerial photographs (Table 5), wooded areas have increased by 152.1% from 1945 to 2007, including close to 41.7% between 1998 and 2007, which constitutes the most rapid change on the temporal scale being studied.

The farmland was progressively abandoned and a woody fringe was reconstituted on its own, now primarily characterized by maple (*Acer rubrum* and *A. saccharum*) and red ash (*Fraxinus pennsylvanica* and *F. nigra*), species typical of the wetlands in this area (Berthelot et al., 2014).

Finally, an examination of the aerial photographs reveals that the expansion of woodland to the expense of farmland occurred progressively, and the forest cover was relatively similar in all three zones. Major differences

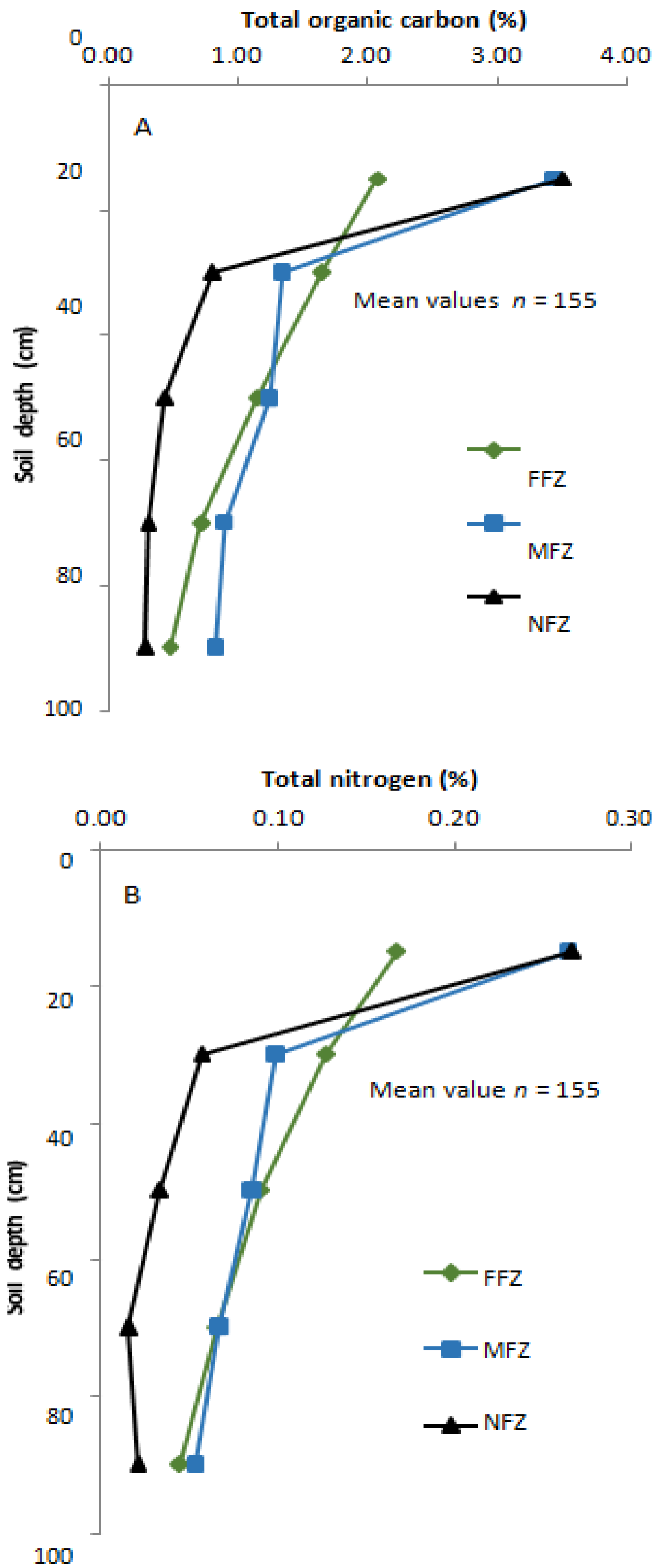

Figure 2. A. Decrease in total organic carbon concentration (TOC%) in the soil profiles (0-100 cm) of the three zones studied (FFZ, MFZ and NFZ); B. Decrease of total nitrogen concentration (TN%) in the soil profiles (0-100 cm) of the three zones studied (FFZ, MFZ and NFZ) (Richmond sector).

Table 4. Correlation between different soil properties (depth of 0-20 cm) in the three zones (FFZ, MFZ, NFZ) in Richmond sector (Southern Québec).

	pH	TOC	TN	Clay	Silt	Sand
pH	1					
TOC (%)	-0.49	1				
TN (%)	-0.40	0.92*	1			
Clay	0.33	-0.30	-0.34	1		
Silt	0.06	-0.33	-0.34	0.61*	1	
Sand	-0.01	0.34	0.36	-0.70*	-0.99*	1

* Correlation is significant at the 0.05 level.

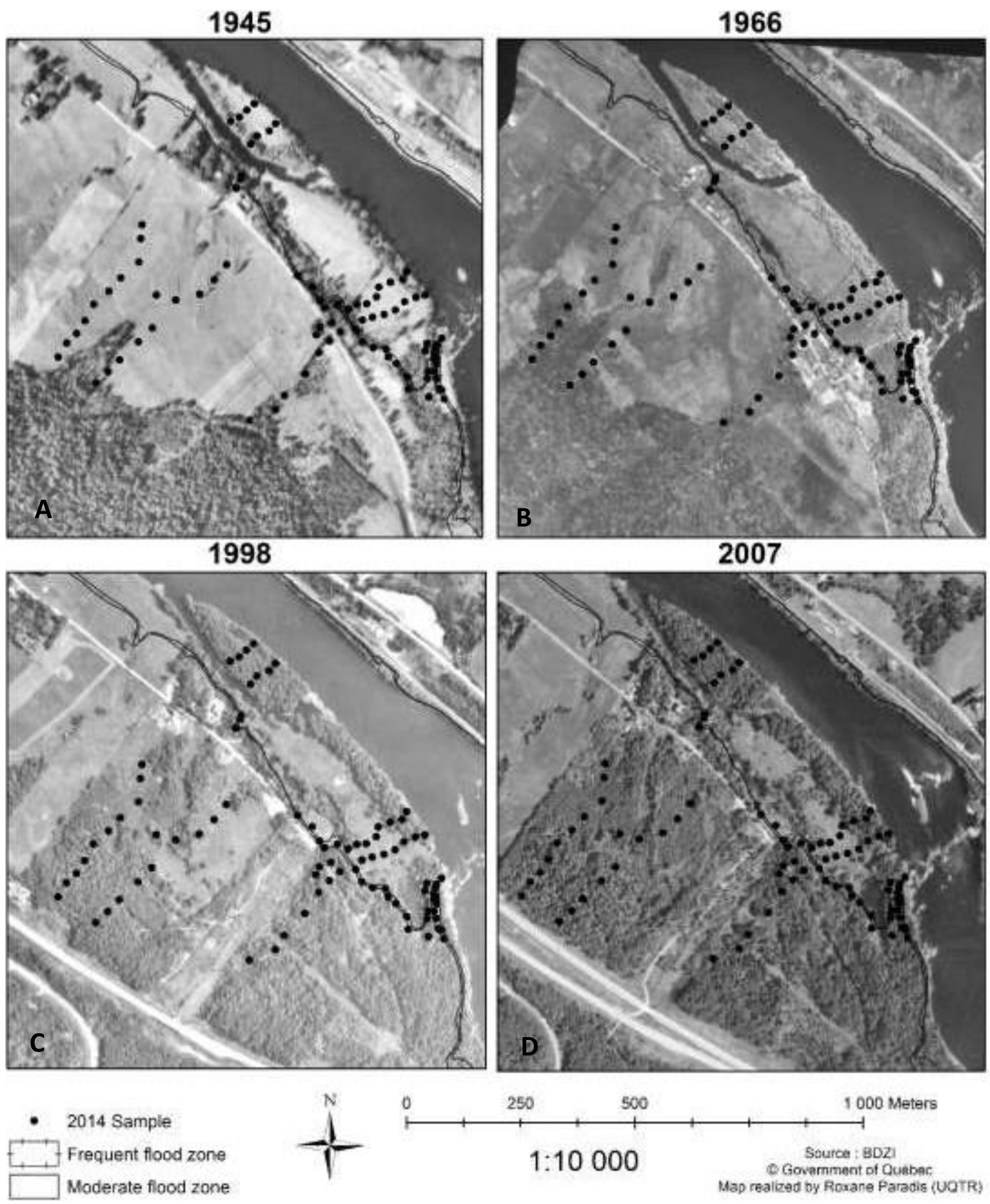

Figure 3. Diachronic analysis of aerial photographs (1945-2007) of the study area in the Richmond sector (left bank of the Saint-François River in southern Québec). A: 1945; B: 1966; C: 1988; D: 2007.

Table 5. Woodland gains in study area between 1945 and 2007 (Richmond sector, southern Québec).

Zone/ year	Woodland areas (m^2)							
	1945	1960	1966	1979	1985	1988	1998	2007
FFz	55.582.41	57.600.45	61.897.26	74.228.43	61.488.83	65.943.39	74.232.86	94.512.79
MFZ	6.603.60	5.606.45	5.681.17	7.817.87	5.548.55	5.992.30	6.401.03	7.998.20
NFZ	136.815.31	117.121.21	129.791.38	194.094.27	208.864.55	248.922.02	278.284.34	400.198.91
Total	199.001.32	180.328.11	197.369.81	276.140.57	275.901.93	320.857.71	358.918.23	502.709.90

The measures are based on the polygonal surfaces drawn from georeferenced aerial photographs.

can be noted in the density or expansion of forest stands based on the three zones being studied, despite the fact that TOC% and TN% concentrations are higher in the NFZ and MFZ. Although the forest cover was basically constituted during the same period for all the zones being studied, it is likely that changes in land use (farmland versus woodland) had no measurable effect on variations in the TOC% and TN% content of the soils analyzed.

DISCUSSION

Variations in soil acidity, bulk density and texture

Soil properties, including pH, bulk density and texture, vary little based on the various alluvial areas being studied. However, there is generally greater variability for soils in the no-flood zones. With respect to pH, the soils in the NFZ zone are generally more acidic than those from the alluvial zones (Table 1). This different soil pH can be attributed to the type of parental material (that is, till and glaciolacustrine deposits) that make up the soil, but also as a result of the type and quantity of litter, which is more substantial in this zone. The presence of litter can contribute to the acidification of soils, particularly for surface horizons (Curtin and Trolove, 2013; D'Acqui et al., 2015). For instance, an increase of SOM in soil surface was related with high soil acidity, and conversely, a substantial decrease in soil pH (by up to 24% in top 7.5 cm) was associated with a decline in SOM following the conversion of permanent pasture to arable cropping in this case (Curtin and Trolove, 2013).

In the no-flood zone, litter has an average thickness of 3.65 cm, compared to 0.80 cm for the frequent flooding zone (FFZ).

It is known that the breakdown of organic matter causes the release of several acidifying compounds, including fulvic and humic acids, as well as humins. Furthermore, the presence of a larger number of coniferous species in the NFZ zone can also cause a decrease in the pH level, given that the breakdown of resinous debris (e.g. lignin, wax) plays a key role in soil acidification (Brady and Weil, 2007).

With respect to bulk density (BD), the NFZ soils have slightly higher average and median values than the floodplain soils (Table 1). However, the results of the statistical tests do not reveal any significant value between the three areas being studied. The variations observed in the NFZ soils can be attributed to the mineral matrices with different origins (parental material), but also the soil structure (granular or subangular forms), which is more apparent in these soils (Gervais-Beaulac, 2013). Lastly, the dominant texture of the surface soils (0-20 cm) in the flood zones (FFZ and MFZ) is mainly silt loam, while sandy loam is the dominant texture in NFZ soils. These soils can also contain gravel or pebbles, while no coarse materials are found in the floodplain soils (>2 mm) in the uppermost part of the profiles (0-100 cm). Fine to very fine sediment (silt and clay) originating from freshet sediment is frequently found in the alluvial zones. The phenomenon of vertical floodplain aggradation (that is, successive deposits of suspended fine sediment during flooding) often accounts for the dominant presence of fine particulate matter such as silt in alluvial soils. This vertical aggradation process maintains the soil in an immature state and hinders its pedological development (Gervais-Beaulac et al., 2013; Saint-Laurent et al., 2014). The constant inflow of flood sediment in fact generates soil profiles that are young and have little chemical alteration, and this provides some vertical homogeneity to alluvial soils (Saint-Laurent et al., 2014). Soils in the no-flood zones have different textural matrices that must be associated with the bedrock, which is basically made up of more varied materials such as till and glaciolacustrine deposits. In fact, part of the NFZ zone is made up of undifferentiated till (that is, glacial deposit without any particular morphology) and glaciolacustrine deposits with shallow water facies (MEMR, 1989). These two types of deposits are more heterogeneous and likely to contain larger proportions of coarser materials (that is, medium sand, gravel, pebbles).

Variation of soil biomass

The average thickness of the litter is significantly lower in the FFZ zone than in the other two zones being studied. In the sites located in the FFZ, only eight were covered with litter and the measured thicknesses were low, that is, 0.80 cm on average (Table 2). In these frequent-flood zones, the litter that accumulates on the surface of the soil during the growing period is most often carried off by the current during floods, leaving the soil stripped bare in the most affected areas (Figure 3). The Richmond area is particularly affected by successive flooding that can occur equally in the spring and the fall. From 1900 to 2015, over 50 flood events were recorded in the Richmond-Windsor area, a certain number of which in the summer and fall, including increased flooding after the 1970s (Appendix). These successive floods prevent the formation of thick litter, thus limiting the inflow of organic matter. Since the main source of soil organic carbon comes from soil biomass, in particular litter, the transfer of nutrients such as OC and N is often inhibited.

The results obtained for TOC% and TN% concentrations in the surface horizons (0-20 cm) confirm that the inflow of organic matter is minimal in the FFZ zone. Higher levels of OC and N are noted in the MFZ zone, which is due to the presence of litter which, although less thick than the litter in the NFZ zone, still allows a sufficient contribution of organic matter for the soil. The average thickness of the litter for the NFZ zone is significantly higher (3.65 cm ±2.95) than for the frequent-flood zone (FFZ) (0.80 cm ±1.66) and provides a constant inflow of organic matter to the soil. Not affected by floods, soil biomass can accumulate over the years, thus ensuring to some extent a permanent source of organic matter. This naturally favours the transfer of nutrients such as OC and N in the soil surface upper layers. The flood zone with a recurrence interval of 20 to 100 years is very similar to the no-flood zone with respect to the results that were obtained.

Similar results were also observed for the flooded or unflooded soils (Cierjacks et al., 2010; Myster, 2015). These authors find that soils are more fertile in less frequently flooded areas and contain more organic matter. Also, the concentration of organic C in the soil horizons increased significantly with distance to the main channel (Cierjacks et al., 2010). Other results show that increased of floods has an impact on decreased of soil fertility and may have effects on forest diversity (Myster, 2015).

Distribution of TOC% and TN% in alluvial soils

In relation to the absence or virtual absence of litter in the FFZ, TOC% and TN% concentrations in the surface layers (0-20 cm) are reduced compared to the other two zones (MFZ and NFZ), which benefit from an inflow of organic matter through the presence of litter (Tables 1 and 2). OC and N concentrations are directly related to the quantity and quality of litter. Since the soils in the FFZ are virtually stripped of litter, it is not surprising to find significantly lower concentrations of TOC% and TN% in these soils subjected to successive flooding. The quantity of litter is significantly greater in the NFZ soils, and the concentrations of these elements are also significantly higher (Table 1). The correlation analysis performed on the various soil properties in fact reveals a strong positive correlation between these two variables (Table 4), showing a close link between these two soil constituents. In fact, it is known that soils with a certain concentration of organic carbon are also rich in nitrogen (Brady and Weil, 2007). Lastly, although the different textural matrices can play a role in the concentration of these two elements (OC and N) within the soil profile (especially for fine-matrice soils such as clay and silt), the correlation analysis did not reveal any significant values between the textural components and the TOC% and NT% variables.

The distribution pattern for TOC% and TN% concentrations is virtually similar at the base of the soil profiles (80-100 cm) for the MFZ and NFZ soils. Since the main sources of organic matter (e.g. leaf litter, rootlets, microorganisms) basically come from the litter and soil surface layers (that is, rhizosphere), it is understandable that higher concentrations are found in the surface horizons (Don et al., 2007). It can be noted, however, that variations between the TOC% and TN% content between the surface horizons and the horizons at the base of the profile are more marked for the MFZ and NFZ soils and have a relatively linear curve for the FFZ soils (Figure 2). The small quantity of litter on these soils in fact hinders the incorporation of organic matter and progressively causes soil depletion.

Conclusion

Marked differences were found with respect to the concentrations of nutrients (organic carbon and nitrogen) in the soils that were analyzed in the various study areas (FFZ, MFZ and NFZ). TOC% and TN% concentrations are significantly lower in the FFZ, while they are higher for the MFZ and especially for the NFZ, as confirmed by the statistical analyses (ANOVA and Tukey test). Litter thickness is also lower in the FFZ than in the other two zones. The stripping of the litter by successive floods in the FFZ creates a direct loss of organic matter, which constitutes one of the main sources of nutrients and has the effect of reducing the quantity of nutrients (that is, TOC% and TN%) in the soil. Since TOC% and TN% are essential elements for soil development and biogeochemical processes, this could have a long-term impact on the vitality of forest stands and their renewal rate. Frequent floods may hinder the establishment of seedlings, which would be vulnerable to the force of the currents, and the seedlings that remain may be burried by flood sediments, thus creating a high risk of mortality for the seedlings.

This study provides a better understanding of the dynamics of alluvial soils of increased flood frequency. If current hydroclimatic changes result in an increase in flood intensity and frequency, a decrease in alluvial soil organic carbon and nitrogen content is to be expected. As a result, the storage of organic carbon in the floodplains is important for maintaining the quality of alluvial soils, quality of alluvial soils, as well as for reducing atmospheric CO_2 and for the vitality of forest stands.

Conflict of Interests

The authors have not declared any conflict of interests.

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