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Stream Corridor Soil Phosphorus Availability in a Forested–Agricultural Mixed Land Use Watershed

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Abstract

Watershed land use affects nutrient and sediment export, particularly through streambank erosion, which can add to P export and contribute to eutrophication in downstream waterbodies. We characterized P of soils from four different land uses (32 sites) along streams in the Missisquoi River basin (Vermont, USA)—silage corn (*Zea mays* L.), hay meadow, emergent wetlands, and forest—and their corresponding streambanks. We measured total P (TP), pH 4.8 NH_4–acetate P, degree of P saturation (DPS), and soluble P. The latter three measurements were used as predictors of potential P bioavailability. Forest soils were relatively low in TP, whereas soils in corn, hay, and wetland were elevated (>1000 mg kg^{-1}). With the exception of forests, the TP of the corresponding streambanks of each land use was statistically significantly lower than in the interior of the land use, while still higher than those in forests, suggesting a possible influence of land use on its adjacent streambank. The pH 4.8 NH_4–acetate P was low in nonagricultural land uses and all streambanks of different land uses, but higher than optimum for soils in cornfields and hayfields. The DPS averaged 36% in the cornfields, but <21% in all of the streambanks. Mean soluble P was 0.14 mg kg^{-1} for corn- and hay-associated streambanks with a DPS <10% but was as high as 3.2 mg kg^{-1} in the agricultural fields. The combination of low bioavailable P measurements indicates that most streambank soils are likely low contributors to P enrichment downstream. However, the elevated TP in some agricultural streambank soils suggests an accumulation of legacy P.

Core Ideas

- Soil P concentrations varied widely among four watershed land uses.
- Agriculture and wetland streambank soils had less P than adjacent land uses.
- Streambank soils from the four different land uses had low P release potential.

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It is well established that land uses within watersheds affect nutrient and sediment loss (Dillon and Kirchner, 1975; Daly et al., 2002; McDowell et al., 2002; Ostrofsky et al., 2018). Agricultural land uses can be significant sources of surface P runoff into receiving waters (Sharpley et al., 1994). In locations with animal agriculture, such as the dairy industry in Vermont, a large net import of P in feed and fertilizer results in a buildup of soil P (Ghebremichael and Watzin, 2011), especially in fields receiving repeated additions of manure. This history of P addition—up to 2- to 10-fold greater than naturally found in forests (Fox et al., 2016)—results in the accumulation of legacy P (Kleinman et al., 2011), which has the potential to be a future source of P export (McDowell and Sharpley, 2001; Sharpley et al., 2009). In contrast, forests and wetlands do not usually have anthropogenic inputs of P, especially when they do not receive runoff from more P-intensive land uses (Houlahan and Findlay, 2004). Mixed use watersheds, therefore, will have variable inputs of nutrients along the streams.

Streambank erosion can be a significant source of watershed P export (Fox et al., 2016), with stream reaches with greater agricultural land use immediately adjacent to streambanks having greater P loss (Zaimes et al., 2008). Studies in mixed land use watersheds have reported contributions of streambank erosion to annual total P (TP) export to be in the range of 10 to 30% of all sources (Kronvang et al., 2012; Ishee et al., 2015), although that contribution can be >90% (Fox et al., 2016). In Vermont's Missisquoi River (a mixed land use subbasin of Lake Champlain), Langendoen et al. (2012) found that >50% of the banks of the main stem and its tributaries were failing and estimated a 36% contribution to watershed TP export. Although P in streambank soils is likely related to adjacent land uses, the role of this relationship on watershed P export has not been reported.

When streambank soils are eroded into the stream, the fresh sediment has the potential to act as a sink or a source of P, depending on factors such as the concentration gradient between water and soil, time of contact, and redox conditions (James and Larson, 2008; Busman et al., 2009). Grundtner et al. (2014) showed that in-stream P adsorption by eroded sediments could explain the high P concentrations found downstream in a receiving water

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Abbreviations: DPS, degree of phosphorus saturation; ICP–OES, inductively coupled plasma–optical emission spectrometer; TP, total phosphorus.

body. Conversely, release of P from sediment can occur from reductive dissolution of Fe-phosphates under anoxic conditions (Dupas et al., 2015). During storms, there is movement of P from the surface soils into stream water (Kerr et al., 2011); however, at stream base flow, the opposite may occur and P can move from the water column into streambank soils or stream sediments, becoming a sink (McDowell and Sharpley, 2001).

Understanding the relationship of soil P concentrations between land uses within a watershed and their corresponding streambanks may improve insight into current and future controls of P export. In Lake Champlain, an international water body bordering the US states of Vermont and New York, as well as Quebec, Canada, P concentrations have increased since P monitoring started in 1990 (Smeltzer et al., 2012). One of the major inputs of P is streambank erosion (Langendoen et al., 2012), a parameter used in calculating total maximum daily loads of P for the Missisquoi River tributary (USEPA, 2016). Here, we seek to shed light on the effect of land use management within the Missisquoi River watershed on soil P properties, both within the given land use and within adjacent streambank soils.

Materials and Methods

Study Area

This study focused on the main stem and Vermont tributaries of the Missisquoi River basin, a 2210-km^2 watershed that includes 612 km^2 in the province of Quebec, Canada (Fig. 1). Major land uses are forests (67.7%), agricultural lands (21.1%), urban (6.7%), and wetlands (1.4%) (Fig. 1). Soil samples were collected from forests, cornfields (*Zea mays* L.), hayfields, and emergent herbaceous wetlands (Table 1). To cover each land use of interest, a total of 32 sites distributed along the Missisquoi River and its tributaries were sampled between May and August 2015 (eight sites per corresponding land use, Fig. 1). The majority of soils were mapped as fluvial Inceptisols (coarse-loamy to coarse-silty Fluvaquentic Endoaquepts and Dystrudepts; Soil Survey Staff, 2017). The goal of site selection was to have the sites distributed evenly throughout the watershed, but the uneven distribution of agricultural land use, along with the necessity to obtain landowner permission, precluded a random distribution of sites. Site selection was done following the 2011 National Land Cover Database from the Multiresolution Land Characteristics Consortium (Homer et al., 2015). Wetlands were water saturated but not flooded when sampling occurred with the exception of site W7. Sampled forests were northern hardwood forests.

At each site (Supplemental Fig. S1), 10 soil samples (10 cm deep) were taken, five within the interior land use and five from the streambank. Interior samples were taken in a straight transect parallel to the stream, with 6 to 10 m between samples, and were separated from the edge of the interior by 10–15 m. Each interior sample consisted of a composite between a central point and four random points located within a 0.3-m radius. Streambank samples consisted of a composite of five points along the vertical

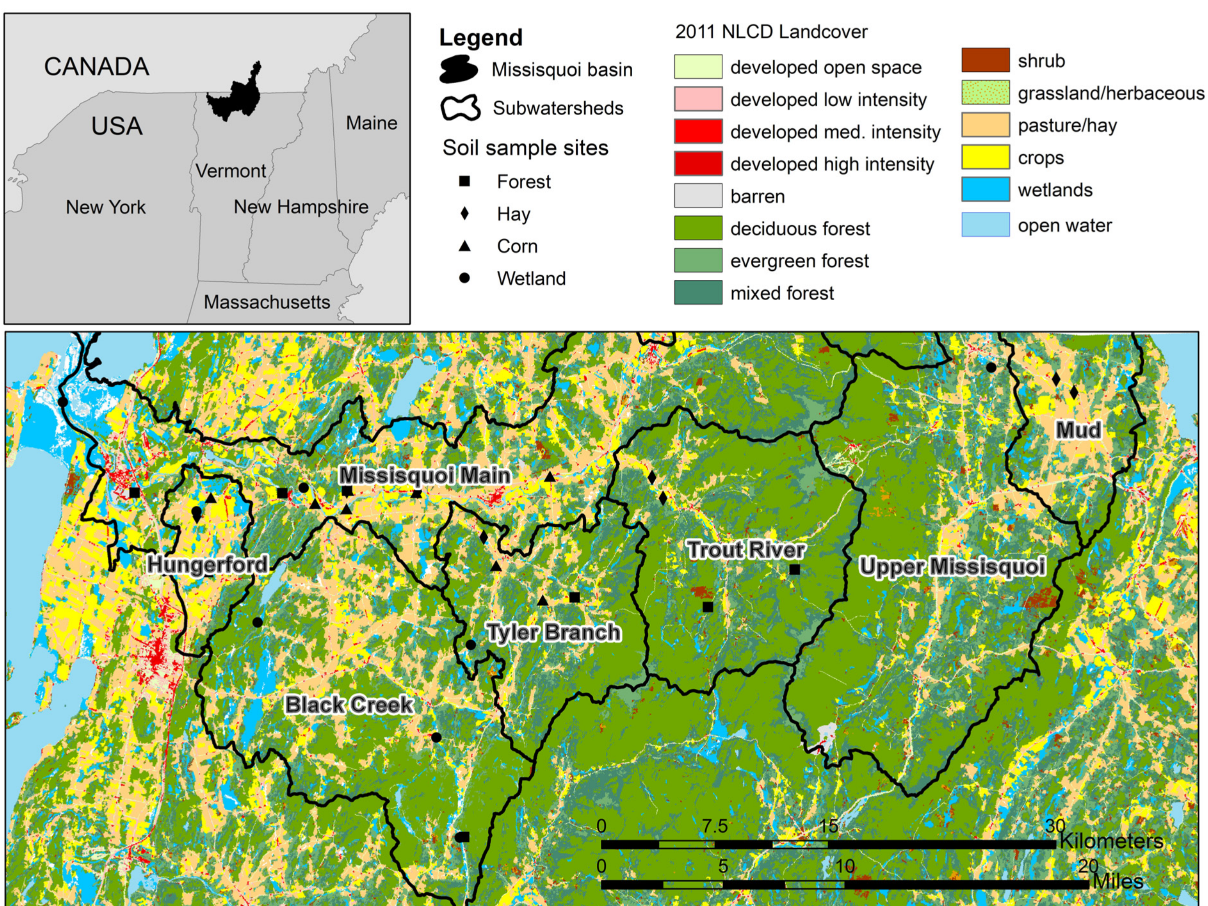

Fig. 1. Missisquoi River watershed and subwatersheds with land-use land cover of the Vermont area of the watershed and distribution of sampling sites in summer 2015 in the Vermont section of the Missisquoi River watershed.

profile, following the same spacing between samples as in the interior transect. Streambank height varied from 0.1 to 6 m. The soil samples taken were then air dried and stored at room temperature. From the total samples collected, 189 (three of the five samples along each transect) were analyzed for texture and TP, whereas all 315 samples were analyzed for pH 4.8 NH_4–acetate P, degree of P saturation (DPS), pH, C content, and N content (see below for methods).

Soil Analysis

To determine TP concentrations, dried soil ground to pass through a 0.5-mm sieve was microwave digested (CEM Corporation) in concentrated HNO_3, and TP was measured with an Optima 3000 DV inductively coupled plasma–optical emission spectrometer (ICP–OES, PerkinElmer) following USEPA Method 3051a (USEPA, 2007). The pH 4.8 NH_4–acetate P (modified Morgan's) extraction (1.25 M acetate) (McIntosh, 1969) was determined using a 1:5 (w/w) soil/solution ratio with 15 min of shaking. Dilute salt-extractable P (soluble P) was determined on corn and hay interior and streambank soils (i.e., half of our sites) using 0.01 M $CaCl_2$ in a 1:10 soil/solution ratio, modified from Self-Davis et al. (2009). Phosphorus determination was performed the same day as extraction. Because air drying and storage can alter P extractability (Turner and Haygarth, 2003), we performed a separate study comparing soluble P in field-moist samples versus air-dried samples and found no significant differences (Supplemental Fig. S2). Phosphorus in all extracts was measured colorimetrically using the Murphy–Riley method (Murphy and Riley, 1962) on a flow injection autoanalyzer (Lachat QuickChem AE, Hach Company). Courchesne and Turmel's (2007) modification of the acid ammonium oxalate extraction was used to obtain oxalate-extractable P, Al, and Fe. Briefly, 0.5 g of dried soil ground to 0.5 mm was extracted with 20 mL of 0.2 M acid ammonium oxalate buffer (pH 3), shaken in the dark for 4 h. Samples were centrifuged at 1500*g* for 8 min, and the supernatant was run on the ICP–OES. The DPS percentage was calculated as P/0.5(Fe + Al), all on a molar basis (Breeuwsma et al., 1995), arbitrarily using the 0.5 multiplier to be consistent with past work in the Lake Champlain basin (Ishee et al., 2015).

Table 1. Site descriptions.

Site	Land use	Subwatershed	Buffer strip width	Buffer strip vegetation	Streambank height	Slope toward streambank	Agricultural land connection to site†
			m		m	°	
F1	Forest	Tyler Branch	–	–	2.0	10.6	NC
F2	Forest	Missisquoi Main	–	–	0.4	4.29	NC
F3	Forest	Missisquoi Main	–	–	0.1	13.83	NC
F4	Forest	Trout River	–	–	0.4	12.64	NC
F5	Forest	Black Creek	–	–	0.5	4.19	NC
F6	Forest	Missisquoi Main	–	–	5.7	10.04	3%S
F7	Forest	Hungerford	–	–	0.5	2.86	NC
F8	Forest	Trout River	–	–	0.5	17.08	NC
W1	Wetland	Hungerford	–	–	2.1	10.52	AU
W2	Wetland	Black Creek	–	–	0.4	4.83	NC
W3	Wetland	Missisquoi Main	–	–	1.4	1.75	NC
W4	Wetland	Upper Missisquoi	–	–	1.1	27.03	AU
W5	Wetland	Black Creek	–	–	0.8	4.15	NC
W6	Wetland	Missisquoi Main	–	–	0.7	3.93	NC
W7	Wetland	Tyler Branch	–	–	–	3.68	NC
W8	Wetland	Black Creek	–	–	0.1	1.62	NC
C1	Corn	Tyler Branch	14	Bushes	0.7	3.84	–
C2	Corn	Missisquoi Main	14	Tall grass	2.5	16.23	–
C3	Corn	Tyler Branch	10	Bushes	0.4	11.18	–
C4	Corn	Missisquoi Main	14	Forested	0.5	6.37	–
C5	Corn	Missisquoi Main	20	Forested–bushes	4.4	20.22	–
C6	Corn	Missisquoi Main	16	Forested–bushes	3.5	20.55	–
C7	Corn	Missisquoi Main	26	Forested–bushes	2.3	7.36	–
C8	Corn	Hungerford	36	Bushes–tall grass	0.6	5.56	–
H1	Hay	Hungerford	0	–	0.1	3.36	–
H2	Hay	Missisquoi Main	25	Forested	0.8	5.24	–
H3	Hay	Missisquoi Main	20	Forested–bushes	2.9	17.75	–
H4	Hay	Tyler Branch	3‡	Forested–bushes	1.6	13.85	–
H5	Hay	Trout River	5‡	Forested	2.1	24.69	–
H6	Hay	Trout River	0	–	2.6	18.72	–
H7	Hay	Mud	20	Forested–bushes	0.7	12.75	–
H8	Hay	Mud	48	Bushes	0.6	12.04	–

† NC, no agricultural land connection with site; AU, agricultural land upstream; 3%S, 3% slope.

‡ Where not eroded.

Particle size was determined on soil sieved to 2 mm, using the hydrometer method (Ashworth et al., 2001). To measure C and N content, subsamples ground to pass through a 0.5-mm sieve were analyzed on an elemental analyzer (FlashEA 1112 NC analyzer, CE Elantech). To measure soil pH, 5 g of dried soil was mixed with 10 mL of distilled water and measured after 30 min with an LE409 pH electrode (Mettler).

Field History and Statistical Analysis

For the agricultural fields, cropping history was obtained either through the farmer's crop consultant or the landowner (Tables 2 and 3). All of the cornfields and five of the eight hayfields were part of active dairy farms and had detailed nutrient management records. The remaining three hay fields were rented or part of smaller farm operations and did not have detailed written records.

Data from the composite samples for each site were aggregated into a single value for the interior and another for its corresponding streambank before analyzing statistical significance ($\alpha < 0.05$) with a repeated-measures ANOVA using a linear mixed model, assuming a compound symmetry covariance structure. For wetland site W7, there was no streambank sample, as it was not possible to find a bank due to flooding conditions. Thus, for wetland statistical analysis, there were only seven streambanks. All statistical analysis was performed using SPSS Statistics 22.0 (IBM Corporation, 2016)

Results

Land Use History

All but one of the corn sites (C7) were in continuous silage corn for at least the prior 10 yr, and all received annual applications of dairy manure ($\sim$34 to 45 m^3 ha^{-1}, equivalent to 30 to 63 kg P ha^{-1}; Tables 2 and 3). Manure was either injected (C1–C3) or incorporated within 2 d of surface application. Five of the cornfields also received 6 to 16 kg ha^{-1} of P banded in started fertilizer. All but one of the hay soils (H1) were continuously in a grass or grass–legume mix for at least 10 yr, and at least six of the fields received annual surface-spread manure additions that ranged from 25 to 46 kg P ha^{-1} (Tables 2 and 3). The two sites not in a continuous crop both had 5-yr rotations of silage corn and grass hay. Because P is not intentionally applied to either forests or wetlands in the watershed, we assumed that no P amendments had been added for at least the past 10 yr.

Soil Characteristics

Soils were generally loamy, with average textures ranging from sandy loams to silt loams (Table 4). The mean sand content in each of the interior land uses was lower than the mean of the associated streambanks. Comparing the interior of each land use, the sand content differed slightly between some of the land uses, with overlaps among most of them (Table 4), whereas for the streambanks, forests had statistically significant higher sand content than emergent wetlands and hay sites. Clay content, in contrast, showed no statistically significant differences between any of the land uses and their corresponding streambanks, with clay content in individual samples ranging from 25 to 330 g kg^{-1} across the four land uses. Mean soil pH ranged from 6.0 to 6.8, except for the forest interior with a pH of 5.54, significantly lower than all other land uses (Table 4). Agricultural soils and their associated streambanks had higher average pH than the other land uses. In general, streambanks had lower C and N content, with the interior of emergent wetlands being the land use with the highest overall (4.6 and 61.6 g kg^{-1} for N and C, respectively).

Phosphorus

The overall mean concentrations of TP across all land uses (interior samples) and across all streambanks were 1026 $\pm$ 304 and 710 $\pm$ 203 mg kg^{-1}, respectively. When analyzing each land use separately (Fig. 2a), only forest soils showed no significant differences in TP concentrations compared with their corresponding streambanks (577 $\pm$ 190 and 563 $\pm$ 112 mg kg^{-1}, respectively). All other land uses had significantly higher values of TP within the land use ($\sim$1200 mg kg^{-1} for cornfields and hayfields, and $\sim$1000 mg kg^{-1} for wetlands) than in streambank soils. There were fewer differences among the streambanks: TP values associated with cornfields and wetlands were significantly higher than those associated with forest streambanks.

Table 2. Agricultural practices in studied cornfields.

Practice	Cornfield							
	C1	C2	C3	C4	C5	C6	C7†	C8
Primary tillage	Disk	Disk	Disk	Chisel	Chisel	Chisel	Chisel	Chisel
Annual P additions via liquid manure (kg ha^{-1})	52	46	35	34	40	30	63	39
Incorporation of manure	Injected	Injected	Injected	Within 2 d	Within 2 d	Within 2 d	Within 2 d	Within 2 d
Annual P additions via banded fertilizer (kg ha^{-1})	0	0	0	13	13	13	16	6

† C7 is in a 5-yr corn–hay rotation. All other corn is continuous.

Table 3. Agricultural practices in studied hayfields.

Practice	Hayfield							
	H1†	H2	H3	H4‡	H5	H6	H7	H8
Years in hay	4	10+	10+	30	20	10+	10+	10+
Type of forage	Grass	Grass	Grass	Grass–legume	Grass–legume	Grass	Grass	Grass
Annual P additions via liquid manure (kg ha–1)	31	29	46	39	0	0	25	29

† H1 is in a 5-yr corn–hay rotation. All other hay is continuous.

‡ H4 also receives annual broadcast additions of 9 kg P ha^{-1}

The interior of agricultural land uses had statistically higher values of pH 4.8 NH_4–acetate P than the interior of forests and emergent wetlands, with means of 18.0 mg kg^{-1} for cornfields and 8.9 mg kg^{-1} for hayfields. Forests and wetlands had no differences in pH 4.8 NH_4–acetate P between the interior and their corresponding streambanks (means were all ~1.5 mg kg^{-1}, Fig. 2b). Individual sites within each land use category followed a similar pattern with few exceptions (Supplemental Fig. S3).

Similar to pH 4.8 NH_4–acetate P concentrations, the interior of forests had a statistically significant lower DPS percentage (~14%) than the interior of all other land uses (Fig. 2c). Emergent wetlands had statistically higher DPS values (22.2%) than forests, whereas agricultural land uses were found to have the highest percentages (36.0% for cornfields and 30.1% for hayfields). Differences between the interior of the land use and their corresponding streambanks were statistically significant only in the cases of agricultural land uses (Fig. 2c). Although the DPS of forested streambanks trended lower than the other land uses (15 vs. 19–21%), there were no significant differences. Individual sites for each land use followed a similar DPS pattern with few exceptions (Supplemental Fig. S4).

Weak-salt-extractable P was only measured in soil samples associated with agriculture. Corn and hay interior samples (1.51 ± 0.16 and 1.40 ± 0.18 mg kg^{-1}, respectively) had significantly higher soluble P than the associated streambanks (0.27 ± 0.06 and 0.19 ± 0.03 mg kg^{-1} respectively). The relationship of soluble P to the DPS (Fig. 3a) revealed a "change point" at 20% DPS, above which the soluble P increased from the <20% baseline of 0.14 mg kg^{-1} in a somewhat weak ($R^2 = 0.43$) but significant ($p < 0.001$) linear fashion. This change point of 20% for DPS is close to the average DPS of the agricultural and wetland streambanks but well above that of the forest samples (Fig. 2c). Soluble P at the low end of the range was better predicted by pH 4.8 NH_4–acetate P (Fig. 3b). For all soils that tested within or below the agronomic optimum range for Vermont (≤7.0 mg kg^{-1}; University of Vermont, Jokela et al., 2018), soluble P was one-tenth of the pH 4.8 NH_4–acetate P ($R^2 = 0.61$, $p < 0.001$). Most of these soils were streambanks, but samples from four hayfields and one cornfield were included.

Discussion

Factors Affecting Total Phosphorus

Studies of native levels of TP in northeastern US parent material and soils, including in riparian soils within Vermont, point to concentrations of 600 to 800 mg TP kg^{-1} in soils relatively low in organic matter (Yang et al., 2013; Ishee et al., 2015; Young and Ross, 2016). For this study, we used three SDs above the average determined nearby by Ishee et al. (2015), or 1172 mg kg^{-1}, to define a local soil that was elevated in TP (assumed to be derived from land management [manure or fertilizer additions]). The agricultural interior sites in our study appear to have legacy P that has nearly doubled the TP status (Fig. 2a). Given typical yields (e.g., 56 Mg ha^{-1}, 35% dry matter) and a crop TP removal rate of 49 kg ha^{-1} (Jokela et al., 2018), we estimate an approximately 30-kg ha^{-1} (15 mg P kg^{-1} soil assuming 2×10^6 kg soil ha^{-1}) annual P surplus at current manure rates for C7 (Tables 2 and 3), requiring roughly 40 yr to achieve the doubling of background soil TP levels observed in agricultural soils of this study. In contrast with C7, current P addition rates on the other corn sites are closer to the estimated crop removal.

In addition to parent material, both soil texture and organic matter can influence TP in soils. As P is a constituent of organic matter (Dalai, 1977), this may partially explain the higher TP in wetland soils. The emergent wetland sites studied did not appear to receive direct runoff from adjacent agricultural fields, as slopes coming from those fields were either flat or angled away from the wetlands (Table 1). However, one site (W8), which had the highest interior TP (1397 mg kg^{-1}) of all wetlands (Supplemental Fig. S5), anecdotally had a history of agricultural use, such that the high TP may be from legacy sources. Elsewhere, Young and Ross (2016) found higher TP in more poorly drained soils with higher organic matter in the riparian zone of a nearby watershed.

Organic matter may also be a factor in the relatively lower TP of the streambank soils of the agricultural land uses, as total C was only 12.3 to 17.3 g kg^{-1} versus 23.0 to 35.8 g kg^{-1} in the interior (Table 4). The streambanks were also higher in sand content than soils from the interior of different land uses, particularly for hayfields, which had almost half the amount of sand than their adjacent streambanks. Investigating riparian soils from nearby watersheds, Young et al. (2012) found that soils classified as sands (≥88%) were lower in TP (<500 mg kg^{-1}). Although differences in particle size may partially explain the relatively lower TP in the nonforest streambank soils, it is most likely that the interior land uses were enriched in TP from legacy sources.

Relationship between Interior Land Use and Adjacent Streambanks

Land uses with higher TP concentrations in the interior had higher levels of TP in the streambank soils (Fig. 2a), although the

Table 4. Soil characterization by land use (data is shown as mean ± SE).

Land use	Transect	N	C	pH	Sand	Silt	Clay	Dominant texture
		g kg^{-1}			g kg^{-1}			
Forest	Interior	2.59 ± 0.64a†	34.41 ± 6.56a	5.54 ± 0.26a	570 ± 46a	318 ± 39a	112 ± 22a	Sandy loam
	Streambank	1.13 ± 0.16A	16.00 ± 3.17A	6.02 ± 0.38A	697 ± 40A	209 ± 34A	94 ± 15A	Sandy loam
Wetland	Interior	4.64 ± 1.11b	61.58 ± 14.33b	6.03 ± 0.23b	314 ± 44b	561 ± 34b	126 ± 25a	Silt loam
	Streambank	2.21 ± 0.43A	31.54 ± 7.03B	5.96 ± 0.12A	470 ± 74B	420 ± 62B	110 ± 26A	Sandy loam
Corn	Interior	2.13 ± 0.22a	23.03 ± 2.77a	6.69 ± 0.48b	515 ± 51ac	402 ± 46ab	83 ± 12a	Sandy loam
	Streambank	2.10 ± 0.73A	17.31 ± 3.38A	6.79 ± 0.17B	656 ± 47AB	271 ± 43AB	72 ± 8A	Sandy loam
Hay	Interior	3.11 ± 0.33ab	35.83 ± 4.26a	6.33 ± 0.21b	320 ± 38bc	539 ± 26b	142 ± 35a	Silt loam
	Streambank	0.99 ± 0.22A	12.26 ± 2.96A	6.41 ± 0.16AB	633 ± 86B	265 ± 71AB	102 ± 30A	Sandy loam

† Statistically significant similarities among different land uses in each location are denoted using the same letters (lowercase and uppercase for interior and streambank, respectively; $p < 0.05$).

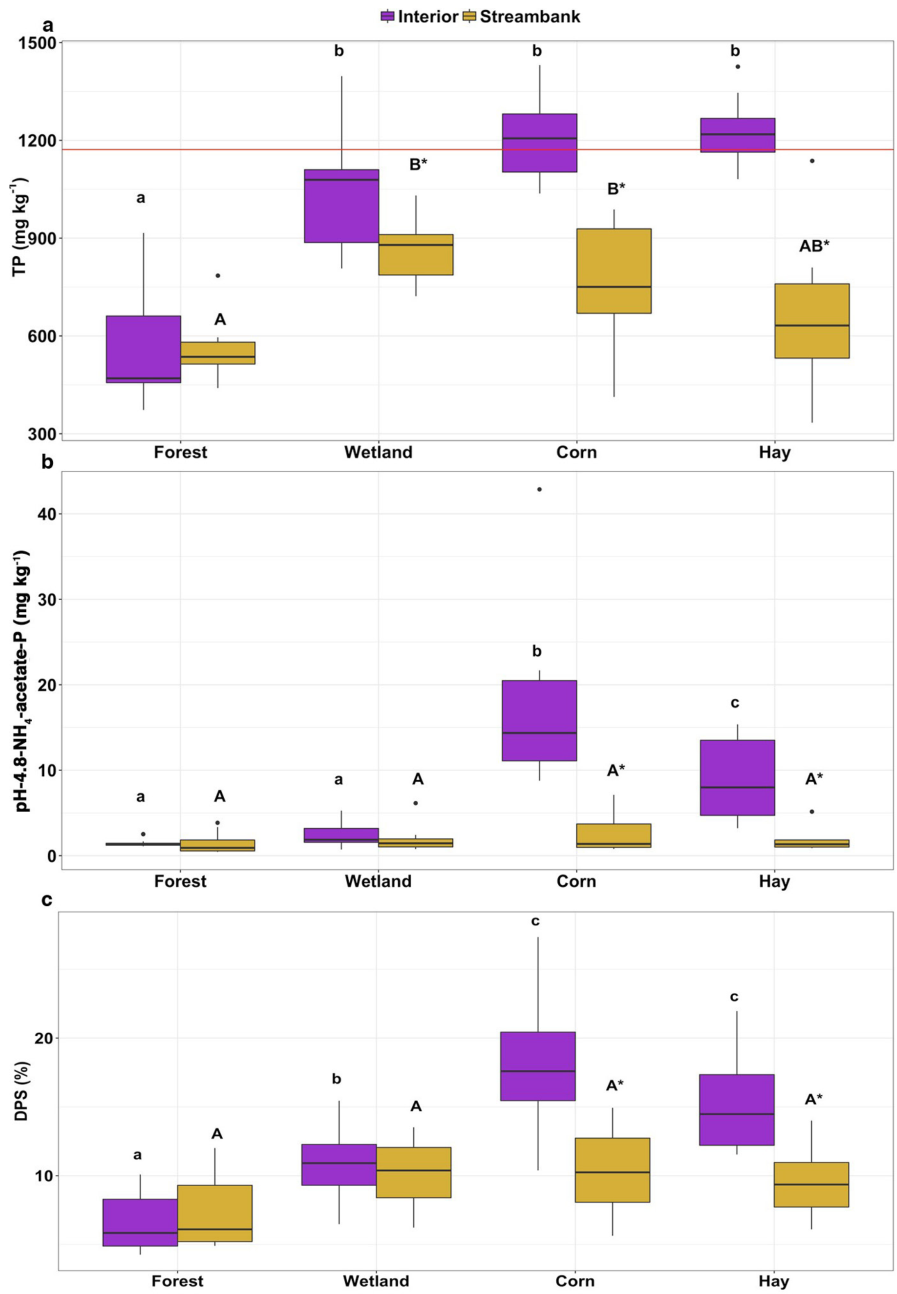

Fig. 2. Differences between (a) total P (TP) concentrations (mg P kg^{-1} soil), (b) modified Morgan's P (mg P kg^{-1} soil), and (c) degree of P saturation (DPS, %) concentrations among the different land uses studied and between their location in the sites (interior or streambank). The median is shown as a bold black line, the third and first quantiles as the upper and lower edges of the boxes (respectively), and the minimum and maximum values as their respective whiskers. Outliers are shown as black dots. The red line in Panel a marks a total *P* value of three SDs higher than the TP soil average for Vermont riparian soils. Statistically significant similarities among different land uses in each location are denoted by the use of the same letters (lowercase and uppercase for interior and streambank, respectively), whereas statistically significant differences between the interior and streambank of the same land use are denoted with an asterisk ($p < 0.05$).

streambank TP concentration for hay was below the 0- to 15-cm riparian soil average found in nearby watersheds by Ishee et al. (2015), and the corn streambank TP was only 13% higher than this average. We conclude that higher TP values of the streambank soils for agricultural sites relative to forest sites cannot unequivocally be assigned to the land use. Even though most of streambank soils were low in P availability indices, TP of some sites does suggest a possible influence of historical agricultural land use on adjacent streambanks. This is supported by the comparison of a corn (C4) and a hay (H2) field adjacent to each other on a river bend and a forest (F2) directly across from both of these agricultural sites (Supplemental Fig. S3–S6). Here, the streambanks of the land uses with anthropogenic P inputs had higher TP concentrations than the streambank of the forest (921, 1137, and 526 mg kg^{-1} for the corn, hay, and forest streambanks, respectively). This change in TP concentration of the streambanks of agricultural lands could potentially be a result of sorption of dissolved P or deposition from P-rich soil particle movement from the interior to the streambank as runoff occurs. The available P values for these agricultural streambank soils were relatively high compared with other agricultural streambank soils (Supplemental Figs. S4 and S5), with the mean DPS for these streambank soils close to the

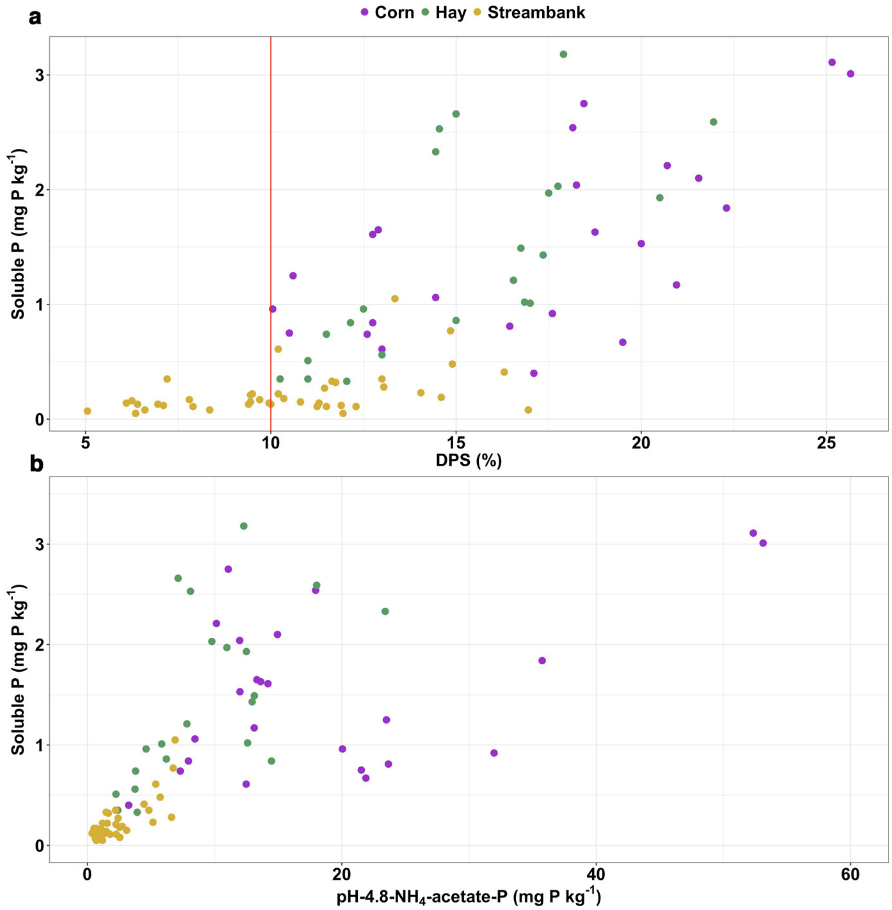

Fig. 3. Soluble P vs. (a) degree of P saturation (DPS, %) and (b) modified Morgan's P (mg P kg^{-1} soil) concentrations among agricultural land uses (corn and hay) and their streambanks. The red line in Panel a marks the 20 % "change point" between soluble P and DPS.

change point of 20%. The combination of relatively higher TP and higher P availability supports the idea that legacy P has accumulated in these particular streambank soils.

Factors Affecting Phosphorus Export

When considered together, the three P availability indicators measured in this study (pH 4.8 NH_4–acetate P, DPS, and soluble P) confirm the high P availability in the agricultural soils and much lower release potential in other land uses, as well as all streambank soils (including those adjacent to agricultural sites). Both the pH 4.8 NH_4–acetate P and DPS were elevated in corn and hay land uses (18.0 mg kg^{-1} and 36% for cornfields, and 8.9 mg kg^{-1} and 30.4% for hayfields, respectively), clearly as the result of legacy sources. The mean pH 4.8 NH_4–acetate P in the different streambank land uses (Fig. 2b) were all below 3 mg kg^{-1}, although a few individual nonforest sites were in or above the agronomic optimum range of 4.1 to 7.0 mg kg^{-1} (Jokela et al., 2018). With the exception of a few individual sites, the DPS and soluble P of streambank soils was low, indicating a low P release potential if eroded.

The large streambank erosion rates and sediment loads being transported into rivers and their tributaries in the Lake Champlain basin and other catchments suggest that sediment-bound P will continue to be a significant concern (Laubel et al., 2003; DeWolfe et al., 2004). Indeed, computational analyses in the Missisquoi Bay suggest that TP losses will still be high even with changing land uses and climate (Zia et al., 2016). The streambank soils of all land uses in the current study generally have a low P release potential and, in some situations, may actually serve as sinks for dissolved forms of P. The interior of cornfields and hayfields, if eroded by extreme weather events, such as happened with Tropical Storm Irene in the northeastern United States in 2011 (Vidon et al., 2018), would most likely contribute to Lake Champlain as sources of P, as they are high in TP and have higher DPS. Clearly, land use strategies that include practices such as exclusionary fencing for cattle and vegetated buffer zones are important to lower the rate of streambank erosion (Laubel et al., 2003; Wynn et al., 2004). However, these riparian strategies will need to be combined with strategies to mitigate upgradient agricultural sources, such as by drawing down soil P (phytomining, tillage, and even P sorbing amendments) and minimizing erosion.

Supplemental Material

The supplemental material includes specific sampling design details, a comparison of P determination between moist and dry soils for weak salt extraction, and average site-specific TP, pH 4.8 NH_4–acetate P, and DPS values.

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Stream Corridor Soil Phosphorus Availability in a Forested–Agricultural Mixed Land Use Watershed

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This article was originally published with inconsistent calculations for the degree of phosphorus saturation (DPS) in Fig. 2c and 3a. The DPS data in these figures were calculated with the formula P/(Fe + Al) but our methods and other data presentation, including text in the caption for Fig. 3, used the formula P/0.5(Fe + Al). The DPS data in those figures should have been twice the values shown. While the use of the 0.5 multiplier may not have a firm basis in theory, we used it to be consistent with our past work in the same watershed. We provide the corrected figures here.

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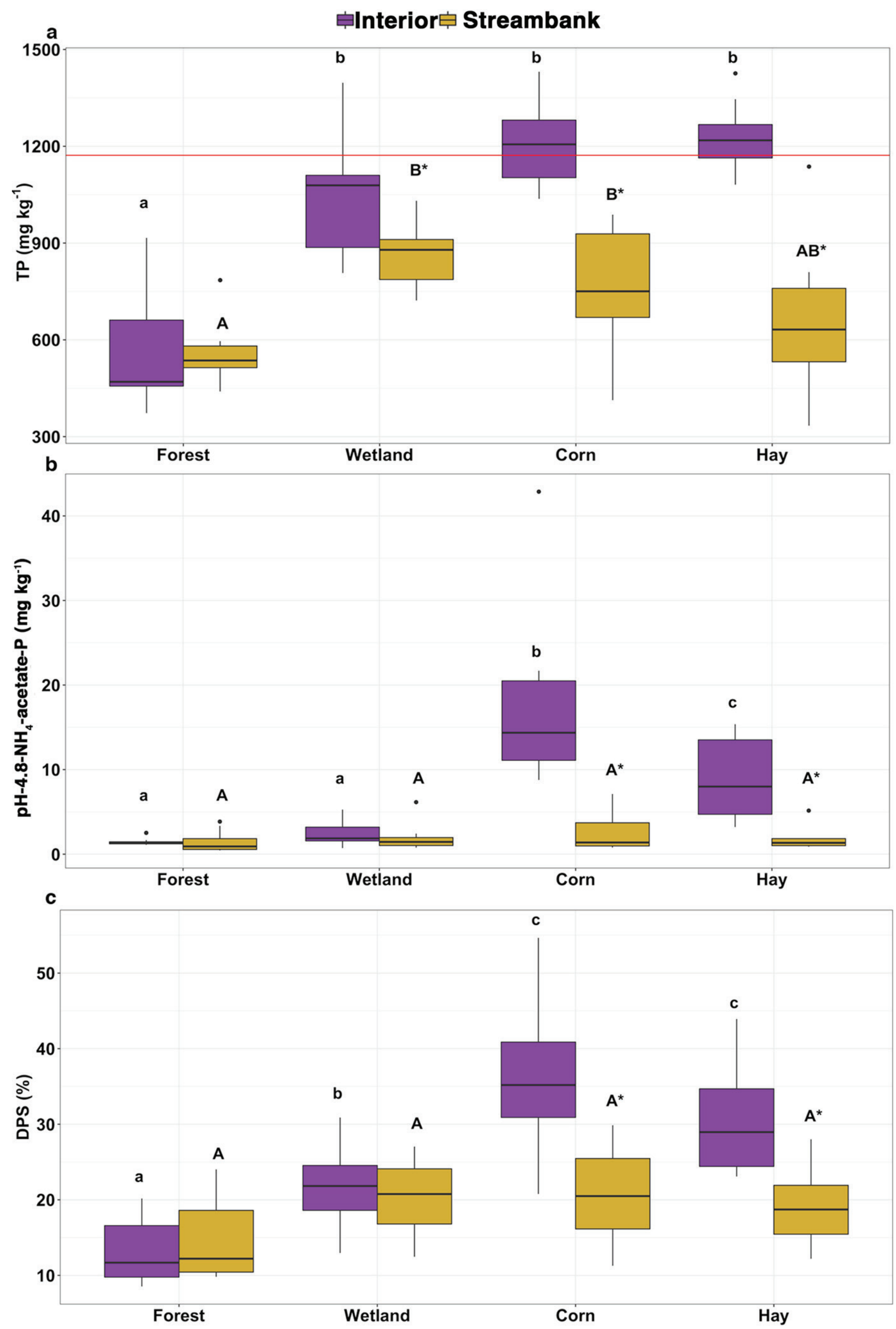

Fig. 2. Differences between (a) total P (TP) concentrations (mg P kg^{-1} soil), (b) modified Morgan's P (mg P kg^{-1} soil), and (c) degree of P saturation (DPS, %) concentrations among the different land uses studied and between their location in the sites (interior or streambank). The median is shown as a bold black line, the third and first quantiles as the upper and lower edges of the boxes (respectively), and the minimum and maximum values as their respective whiskers. Outliers are shown as black dots. The red line in Panel a marks a total *P* value of three SDs higher than the TP soil average for Vermont riparian soils. Statistically significant similarities among different land uses in each location are denoted by the use of the same letters (lowercase and uppercase for interior and streambank, respectively), whereas statistically significant differences between the interior and streambank of the same land use are denoted with an asterisk ($p < 0.05$).

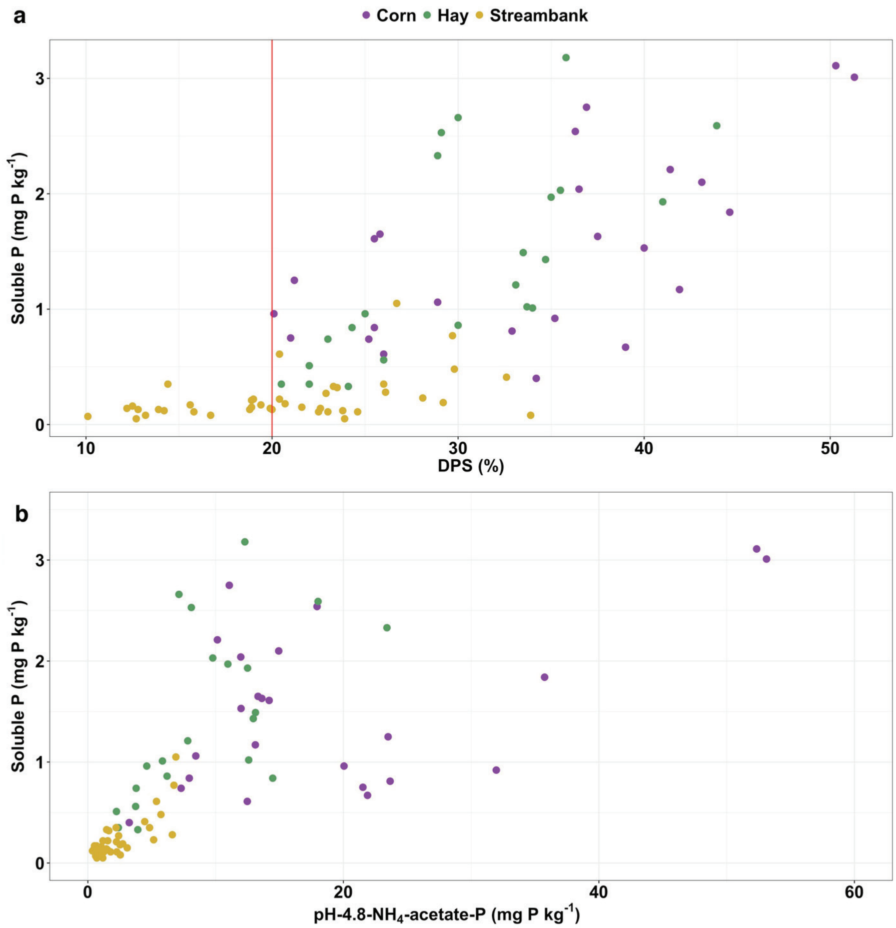

Fig. 3. Soluble P vs. (a) degree of P saturation (DPS, %) and (b) modified Morgan's P (mg P kg^{-1} soil) concentrations among agricultural land uses (corn and hay) and their streambanks. The red line in Panel a marks the 20% "change point" between soluble P and DPS.