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Abstract: Riparian buffer strips (RBS) may protect surface water and groundwater in agricultural settings, although their effectiveness, observed in field-scale studies, may not extend to a watershed scale. Hydrologically-controlled leaching plots have often shown RBS to be effective at buffering nutrients and pesticides, but uncontrolled field studies have sometimes suggested limited effectiveness. The limited RBS effectiveness may be explained by the spatiotemporal hydrological heterogeneity near non-irrigated fields. This hypothesis was tested in conventional corn and soy fields in the St. Lawrence Lowlands of southern Quebec (Canada), where spring melt brings heavy and rapid runoff, while summer months are hot and dry. One field with a mineral soil (Saint-Roch-de-l'Achigan) and another with an organic-rich soil (Boisbriand) were equipped with passive runoff collectors, suction cup lysimeters, and piezometers placed before and after a 3 m-wide RBS, and monitored from 2011 to 2014. Soil topography of the RBS was mapped to a 1 cm vertical precision and a 50 cm sampling grid. On average, surface runoff intersects the RBS perpendicularly, but is subject to substantial local heterogeneity. Groundwater saturates the root zones, but flows little at the time of snowmelt. Groundwater flow is not consistently perpendicular to the RBS, and may reverse, flowing from stream to field under low water flow regimes with stream-aquifer connectivity, thus affecting RBS effectiveness calculations. Groundwater flow direction can be influenced by stratigraphy, local soil hydraulic properties, and historical modification of the agricultural stream beds. Understanding the spatiotemporal heterogeneity of surface and groundwater flows is essential to correctly assess the effectiveness of RBS in intercepting agro-chemical pollution. The implicit assumption that water flows across vegetated RBS, from the field to the stream, should always be verified.

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Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

Highlights

- Riparian Buffer Strips (RBS) efficiency statistics differ in uncontrolled plots.
- Surface runoff may deviate from perpendicular flow assumptions across RBS plots.
- Pooling pollutants concentrations at field margin may buffer local heterogeneities.
- Greater microbasins may not yield greater runoff volumes across the RBS.
- Groundwater flow reversal in summer may influence perceived RBS effectiveness.

Hydrological Heterogeneity in Agricultural Riparian Buffer Strips

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[†] Abbreviations: Riparian buffer strips (RBS); Herbaceous vegetation treatment (CX); *Salix miyabeana* SX64 at 33 333 stumps/ha (3X); *Salix miyabeana* SX64 at 55 556 stems/ha (5X); Saint-Roch-de-l'Achigan (SR); Boisbriand (BB); saturated hydraulic conductivity (K_{sat}); Ministère de l'Agriculture, des pêcheries et de l'alimentation [Ministry of Agriculture, fisheries and food] MAPAQ; Degree-days of growth ($^{o}C\cdot d$); edge-of-field (CF); middle of the buffer strip (CC); close to the river (CR); in the field (CS); high density polyethylene (HDPE); polyvinyl chloride (PVC); Global positioning system (GPS); differential Global positioning system (dGPS); Digital elevation model (DEM); Angle of incidence (θ_{CF} and θ_{CR}) measured in degrees (^{o}); deviation from a perpendicular transect ($\theta\perp_{CF}$ and $\theta\perp_{CR}$); Identity (ID); Triangulated irregular network (TIN).

Abstract

Riparian buffer strips (RBS) may protect surface water and groundwater in agricultural settings, although their effectiveness, observed in field-scale studies, may not extend to a watershed scale. Hydrologically-controlled leaching plots have often shown RBS to be effective at buffering nutrients and pesticides, but uncontrolled field studies have sometimes suggested limited effectiveness. The limited RBS effectiveness may be explained by the spatiotemporal hydrological heterogeneity near non-irrigated fields. This hypothesis was tested in conventional corn and soy fields in the St. Lawrence Lowlands of southern Quebec (Canada), where spring melt brings heavy and rapid runoff, while summer months are hot and dry. One field with a mineral soil (Saint-Roch-de-l'Achigan) and another with an organic-rich soil (Boisbriand) were equipped with passive runoff collectors, suction cup lysimeters, and piezometers placed before and after a 3 m-wide RBS, and monitored from 2011 to 2014. Soil topography of the RBS was mapped to a 1 cm vertical precision and a 50 cm sampling grid. On average, surface runoff intersects the RBS perpendicularly, but is subject to substantial local heterogeneity. Groundwater saturates the root zones, but flows little at the time of snowmelt. Groundwater flow is not consistently perpendicular to the RBS, and may reverse, flowing from stream to field under low water flow regimes with stream-aquifer connectivity, thus affecting RBS effectiveness calculations. Groundwater flow direction can be influenced by stratigraphy, local soil hydraulic properties, and historical modification of the agricultural stream beds. Understanding the spatiotemporal heterogeneity of surface and groundwater flows is essential to correctly assess the effectiveness of RBS in intercepting agro-chemical pollution. The

implicit assumption that water flows across vegetated RBS, from the field to the stream, should always be verified.

Keywords

Riparian buffer strips; surface water; groundwater; agricultural watersheds; runoff; spatiotemporal heterogeneity; microbasins

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1. Introduction

Riparian buffer strips (RBS) are one of several best management practices for the protection of surface water (Moore et al. 2008; Bentrup 2008), and are recommended in agricultural settings around the world to mitigate non-point source pollution (Hickey and Doran 2004; Smethurst et al. 2009). However, narrow RBSare not always effective (Mayer et al. 2006), as demonstrated in a recent study of RBS bordering corn and soy fields in southern Québec (Canada). There, site, season, and depth were all found to influence the effectiveness of total phosphorus and nitrate removal, while ammonium and dissolved phosphate removal was generally ineffective (Hénault-Ethier et al. 2016, Submitted-c). Glyphosate, the most common active ingredient in herbicides around the world (Health Canada 2011; EPA 2011; Eurostat and European Comission 2007), was also not consistently removed by the RBS (Hénault-Ethier et al. 2016, Submitted-b). In runoff, neither glyphosate nor aminomethyl phosphonic acid (AMPA), its main degradate, were significantly removed by the RBS, although soil analyses (0-20 cm) suggest some buffering of the solid-bound herbicide. These reports of limited RBS effectiveness are not uncommon in the literature, and several explanations have been proposed.

From a hydrological perspective, RBS effectiveness is influenced by precipitation, flow convergence, infiltration rate, water storage capacity, topography, and vegetation cover (Polyakov et al. 2005). Wider RBS often appear to more effectively remove nutrients than narrow RBS (Mayer et al. 2006; Vought et al. 1994). However, narrow RBS are common in several regions (Dagenais 2015), including in the province of Québec (Canada) (MDDEP

2005). These narrow RBS have been shown to improve water quality (Norris 1993; Wenger 1999), although their effectiveness is highly variable in differing environments (Hickey and Doran 2004). Seasonality may not affect RBS effectiveness where annual climate fluctuations are weaker, such as in many European settings (Sabater et al. 2003), but are known to affect RBS effectiveness at northern latitudes, such as in Québec (Gasser et al. 2013; Hénault-Ethier et al. 2016, Submitted-b; Hénault-Ethier et al. 2016, Submitted-c).

RBS vegetation may enhance infiltration (Dosskey et al. 2010), deposition of sediment (Polyakov et al. 2005), and soil-bound agro-chemicals (Krutz et al. 2005). Because grasses disperse convergent overland flows (Lowrance et al. 1997; Dosskey et al. 2010), grassy RBS may buffer surface runoff more effectively than forested RBS (Lyons et al. 2000). Shrubby vegetation promotes evapotranspiration (Allen et al. 1998; Dosskey et al. 2010), and herbaceous vegetation may therefore be as effective as shrubby vegetation in intercepting nutrients or glyphosate (Hénault-Ethier et al. 2016, Submitted-c; Mayer et al. 2007; Hénault-Ethier et al. 2016, Submitted-b). However, RBS efficiency related to vegetation cover may be inconsistent across sites (Dosskey 2001; Dosskey et al. 2010; Correll 1996; Lyons et al. 2000; Hénault-Ethier et al. 2016, Submitted-c). Vegetation type, density, and spacing can influence soil porosity (Dosskey et al. 2010) and sediment interception by the RBS (Polyakov et al. 2005), but is not always the case (Hénault-Ethier et al. 2016, Submitted-b; Hénault-Ethier et al. 2016, Submitted-c); other factors influencing RBS effectiveness must be identified.

Subsurface drainage may contribute to the direct exporting of nutrients (i.e., P, King et al., 2015), effectively bypassing vegetated buffer strips (Osborne and Kovacic 1993). Tile drainage can be present over 5 to 100% of temperate and boreal zones of the Northern Hemisphere (McCorvie and Lant 1993; Zucker and Brown 1998; King et al. 2015; Harker et al. 2004; Herzon and Helenius 2008).

The spatial scale at which studies are carried out may also affect their resulting effectiveness. Most studies relying on runoff plots and confined field experiments demonstrate some effectiveness in filtering a variety of contaminants from runoff (Norris 1993). Counterintuitively, agricultural catchment studies often find limited RBS effectiveness in controlling surface water pollution, despite general success at the plot scale (Norris 1993; Verstraeten et al. 2006; Stutter et al. 2012). For this reason, uncontrolled field studies, under existing agricultural activity and natural precipitation regimes, and without hydrological boundaries between individual plots, are necessary to truly appreciate the potential real-life effectiveness of RBS. Since runoff and groundwater flow are often difficult to measure in uncontrolled settings (Krutz et al. 2005), assessing RBS effectiveness in agricultural catchments requires greater spatiotemporal characterization. Assessing hydrologic flowpaths together with chemical and biological processes is essential to better understand riparian zone functioning (Hill 2000).

This study was performed to assess additional processes that control runoff and groundwater flow, and which might explain low RBS effectiveness. The work was carried out on experimental corn and soy fields in the St. Lawrence Lowlands of southern Québec (Canada), where low nutrient (Hénault-Ethier et al. 2016, Submitted-c) and glyphosphate (Hénault-Ethier et al. 2016, Submitted-b) retention of 3 m-wide RBS was recently observed. Factors which may impact the hydrology and hydrogeology of the fields and associated RBS or the interception of surface runoff and groundwater by the RBS were identified. The specific objective was to assess the spatiotemporal hydrological heterogeneity, so as to determine whether it may have affected the outcome of earlier RBS studies. Topographic, stratigraphic, and pedologic site characterization was performed on the two sites (Boisbriand and Saint-Roch-de-l'Achigan), so as to quantify the homogeneity of slopes, strata, and soil physical properties. The spatial heterogeneity of surface runoff and the temporal variation of groundwater flow were assessed. Finally, the potential of RBS runoff interception was estimated, and the contributing field areas were measured to assess their edge-of-field runoff collection potential.

2 Methods

2.1 Experimental sites

The experimental design of both sites is a triplicate randomized block, with three treatments each: herbaceous vegetation (CX), and *Salix miyabeana* (willow) SX64 at 33,333 (3X) and at 55,556 stems/ha (5X). The two experimental sites (Figure 1), where corn and soy were alternately cropped from 2011-2013, border two first order streams. The Moïse-Dupras stream in Saint-Roch-de-l'Achigan (SR: N45°50'48.3"; W73° 36'16.7"; alt. 46 m) flows towards the L'Achigan River, 1.3 km downstream from the site. The Dumontier stream in Boisbriand (BB: N 45°36'39.8", W 73°51'40.3"; alt. 44 m) reaches the Des-Milles-Isles river 4.8 km downstream. SR has a relatively flat topography, with a 3 m deep artificially dug drainage ditch, while BB has a gently hilly topography (15 m difference in elevation from the top of the field, 100 m inland, to the Dumontier stream). The Dumontier stream has been straightened since the

1930s, and flows through an ancient wetland, as documented by aerial photographs of the site (Figure S1).

Meteorological data from the Sainte-Thérèse Ouest (6.8 km from BB) and L'Assomption (13.8 km from SR) weather stations were used (Lepage and Bourgeois 2011). From 2010 to 2013, mean annual temperature was 7.5 °C and 7.0 °C, degree days of growth were 990 °C·d and 989 °C·d, and annual precipitation was 1034 and 1121 mm for BB and SR respectively (see Hénault-Ethier et al. 2016, Submitted-a).

2.2 Surface water and groundwater sampling

A total of 36 surface water collectors, 72 lysimeters, and 24 piezometers were installed on either side of the RBS, at the field edges (CF acting as a reference) and close to the river (CR) (Figure 1), and were sampled as described in Hénault-Ethier et al. (2016, Submitted-c). Surface runoff was collected in high density polyethylene (HDPE) buckets, buried to three quarters of their height in the ground. These were fitted with polyvinyl chloride (PVC) gutters to shelter them from rain, extended from the soil surface, perpendicular to the buffer strip, over a length of 60 cm, and were equipped with 2 mm nylon mesh to filter coarse particles. At the time of sampling, the total volume of water collected was estimated *in situ*, measuring collected water depth with a ruler. A statistical analysis was conducted to check whether the collected runoff volume was significantly different between sites and/or was influenced by which side of the RBS it was collected from (CF vs. CR). Soil water was collected in polyvinyl chloride suction lysimeters (Soil Moisture Equipment Inc, 1900L, Santa Barbara, CA, USA) equipped with ceramic cups buried at 35 or 70 cm depth. Groundwater levels were recorded manually during every water sampling campaign from 2011-2014 (± 0.5 cm). The piezometers (3 m long x 3.7 cm diameter PVC tubes, strainer 60 cm long with 0.5 cm holes) were installed in the outer margin of each RBS field block, which comprised the three treatments described above.

2.3 Topography, slopes, and microbasins

The precise topography of the buffer strips and neighboring fields was obtained in July 2011 using a differential GPS (dGPS), with a base fixed near the center of the study area (Trimble, R8GNN base and rover, Sunnyvale, California, USA). The vertical precision of the instrument is approximately 1 cm (USGS (United States Geological Survey) 2013). The sites were surveyed every 0.5 m to determine the exact positions of the water collecting devices, soil cores, and buffer strip margins, and to account for important hydrological features (e.g., engineered passages to improve drainage from field to stream, or other obvious flow paths). A coarser sampling interval (~15 m grid) was used over the proximal regions of the adjacent fields to determine the area drained by each experimental buffer strip. Finally, regional digital elevation models (DEMs) were used to confirm flow directions over the width of the whole field. The regional DEM for BB was obtained from the database of the local watershed committee (Louis Tremblay, Comité de Bassin Versant de la Rivière des Milles-Isles (COBAMIL), personal communication), and was obtained for SR from the regional municipality geomatic services office (Adam Pelletier, MRC Montcalm, personal communication). To improve results, the regional 1:50 000 DEM was transformed into vector data (isolines), so it could be interpolated.

DEMS at three spatial scales were created using ArcGIS (version 2.1.4, Esri, Redlands, California, USA) (Figure S2,d-f) to visualize the terrain, understand where surface runoff would flow, and estimate from what surface area of the field runoff was collected and would be intercepted by the RBS. The finest, or *RBS*, scale (1:250; obtained with the 0.5 m sampling grid using the dGPS) had a vertical precision of 1 cm, a horizontal precision of 10 cm, and resolution of 10 cm. The intermediate, or *proximal*, scale (1:1000; obtained with the 15 m grid sampling using the dGPS) had a vertical precision of 1 m, a horizontal precision of 10 m, and a resolution of 1.5 m. Finally, the coarsest, or *field*, scale (1:30 000; obtained by resampling the regional DEMs) had a vertical precision of 1 m, a horizontal precision of 10 m, and a resolution of 1.5 m. Slopes within the RBS were calculated using the z-values of pairs of water sampling equipment from the CF and the corresponding CR sides of the RBS. Slopes further in-field were estimated by extending a 5 m transect from the CF sampling equipment into the field at a 90^{o} angle relative to the stream, and extracting the corresponding point value from the DEM. The homogeneity of slopes across sites and treatments was tested statistically with an ANOVA on site (BB vs. SR), treatment (CX vs. 3X vs. 5X), and interaction. As for all statistical analyses, when data did not conform to the normality assumption, non-parametric, rank-based tests were conducted, using JMP 7 (SAS Institute, Cary, NC).

2.4 Surface runoff and basins

The r.watershed tool of GRASS GIS (version 6.0, Champaign, Illinois, USA) was used for basin visualization and flow channel definition. The minimum basin size was set to allow for the approximation of flow channels in as much details as possible without overcrowding the visualization.

In a second phase, the smoothed DEM was used as the input in ArcHydro Basic Dendritic Terrain Processing (version 2.0, ESRI, Redlands, California, USA). The correct positions of the stream and drainage ditch were set in the model. The input DEM was reconditioned using the AGREE method (Hellweger and Maidment 1997) in the ArcHydro extension (Version 2.0 beta), using the "fill sinks" function to smooth the surface. Surface water flow directions were mapped using the three resolutions of DEM created above (*RBS*, *proximal,* and *field*). Using the proximal scale DEM, drainage line angles of incidence between the RBS and flow path directions, and the topographical microbasins were calculated.

The drainage line angles of incidence (º) with the RBS were estimated using a protractor on both edges of the RBS (θ_{CF} and θ_{CR}), as illustrated in Figure 2. The corresponding deviation from a perpendicular transect ($\theta_{\perp CF}$ and $\theta_{\perp CR}$) was then calculated to account for drainage lines which change direction as they cross the RBS. The similarity of the incidence angles was verified statistically with an ANOVA on side (CF vs. CR), treatment (CX vs. 3X vs. 5X) and interaction.

The area of the microbasins draining toward the surface water collectors in each experimental buffer strip was computed in ArcGIS. Four methods were used to estimate the microbasin drainage areas: *Basins* (catchment — surface drained by smaller arms of the drainage lines), *Nearest Stream*, *Affiliated Basins* (BB only; includes several smaller basins — adjunct catchment — and larger ramifications of the runoff)), and drainage points (SR only, manually located points positioned on the drainage lines — e.g., passages engineered to favor drainage from fields to stream — from which the software computes drainage surface). The homogeneity of the drainage microbasins was verified statistically. The ''basins'' and ''closest streams'' microbasin surface areas were tested with an ANOVA on site (BB vs. SR), treatment (CX vs. 3X vs. 5X) and interaction. The ''affiliated basins'' in BB and passages engineered to favor drainage, ''drainage points'' in SR, were log transformed to obtain data normality, and analyzed for treatment effect with ANOVA.

2.5 Groundwater level and flow

To assess whether the lysimeters were installed in unsaturated soil, water table depths from the RBS piezometers were interpolated in ArcGIS. A lysimeter was considered to be submerged when the water table level was at least 10 cm above the ceramic porous cup (accounting for z-measurement precision). In BB, a scenario for which the water table was connected to the stream was tested in addition to the RBS interpolations, due to the presence of a visible discharge zone in the eastern section of the RBS. Connectivity was introduced by forcing stream water level in the groundwater interpolation. Water table depths near each water sampling equipment were then tabulated. Groundwater flow direction was estimated based on head differences (z_{CF}-z_{CR}). Groundwater flow was considered directional only if the difference in elevation from the CF to CR sides of the RBS was greater than 20 cm (accounting for two times z-measurement precision).

2.6 Stratigraphy

The buffer strips were established in a typical humisol in BB (derived from an ancient wetland) and in a mineral sandy clay-loam sitting atop a clay bed in SR. Soil granulometry was characterized at the surface and at 35 cm depth (Table 1), using the wet sifting method adapted from CEAEQ (2010) on 1000 cm^3 samples obtained from field and RBS push cores (10 cm diameter) for each site. The BB neighboring field drainage ranges from good to imperfect, while SR is imperfectly drained (Gagné et al. 2013). Because BB soil in the vicinity of the RBS was very different from that of the rest of the field, *in situ* Guelph permeameter (Soil Moisture, Model 2800K1, Santa Barbara, CA, USA) measurements of the saturated hydraulic conductivity (K_{sat}) were conducted for the surface soils (0-10 cm). The K_{sat} of the other soil types mapped within the limits of the BB and SR fields were obtained from the literature (Gagné et al. 2013; MAPAQ 1990).

The stratigraphy was characterized for every 10 cm depth during the installation of the water collecting devices in May 2011, and was completed with soil cores extracted using a 10 cm diameter x 20 cm depth auger during water sampling campaigns from 2011-2013. Soil cores were collected near the stream (CR), in the middle of the buffer strip (CC), next to the buffer on the side of the field (CF), and in the field itself (CS), at a minimum distance of 1.5 m from the water sampling equipment to minimize disturbance. Granulometric observations, compaction, and color (Munsell Soil Color chart) were used to classify the collected samples. A 3D representation of the sites was built using GMS (v10.0, Aquaveo™, Provo, Utah, USA). Each borehole was assigned a soil ID, as well as a horizon ID at the contact between the layers.

Cross-sections were automatically generated and filled. The GPS data was used to generate a Triangulated irregular network (TIN) with linear interpolation. Transects were manually centered on the CF-CR axis, and centered mid-distance on each RBS, where the water sampling equipment is located.

3. Results and Discussion

3.1 Topography

Slopes are important predictors of RBS effectiveness (Bentrup 2008). Slopes within the two sites' RBS are greater than 0.5 - 2 %. In the vicinity of the RBS (up to 5 m into the field), slopes in BB vary from 0 to 5%, while they vary from 0 to more than 15 % in SR. Approximately 50 % of the terrain is nearly level (> 0.5 - 2 %) at both sites (Figure 3). The broader range of estimated slopes in SR is caused by localized minor mounts and small depressions, the terrain being much more level at the field scale than is BB. Topographic minima and maxima in SR are 48.4 and 54.2 m respectively, with a sharp > 2 m drop from the riverside buffer (CR) edge to the actual stream level. In BB, the minima and maxima are 35.7 and 41.9 m respectively, but the major difference in elevation is within the field, the drop from the buffer edge nearest the stream (CR) to the stream being less than 0.5 m. Overall, neither site ($p = 0.9400$) nor the RBS vegetation treatment ($p = 0.0723$) had statistically different slopes. However, absolute slopes (which can affect residence time, but are independent of slope direction) were significantly lower in BB ($p = 0.0008$*), and there was a significant interaction with the RBS vegetation treatment ($p = 0.0032$*). Within the RBS, we did not observe slopes of greater than 6 %, which may fail to retain sediments (Polyakov et al. 2005) because they lead to higher overland flow velocity while minimizing infiltration and particle deposition (Knies 2009). Because slopes were relatively low and uniform across the sites, RBS sides, and treatments (despite some variability in absolute slopes), slope may not have been a primary driver for the limited RBS effectiveness in mitigating nutrient and glyphosate transport observed, and may not be a primary determinant for the lack of difference observed between the treatments.

3.2 Surface runoff

Drainage lines at the *RBS*, *proximal*, and *field* scales (Figure S2, a-c) appear generally to be consistent (Figure S3). The *proximal* and *field* scales in SR in particular are almost exactly superimposed within the model limits. The *RBS* scale was modeled with 10X greater precision (± 0.1 m) than the *proximal* scale, and there are likely several hydrologic flowpaths across the RBS, and perhaps not only nearly-unique concentrated flow paths as suggested at the other scales. The larger the scale, the more likely realistic values will be obtained due to the levelling out of minor spatial heterogeneities, but also the more likely micro-site specific process variability will be lost due to this same effect (Krutz et al. 2005). The narrow limits of the *RBS* scale lead to several potential hydrologic flowpath artifacts (i.e., water appearing to drain from the RBS to the field, contrary to the other modeled scales; small and unconnected drainage lines intercepted by the RBS model limits). Furthermore, the finer drainage lines output at the fine *RBS* scale are likely to change with time. Therefore, the fine *RBS* scale may not be very instructive for the purpose of modeling runoff over the order of a few years necessary to quantify nutrient ((Hénault-Ethier et al. 2016, Submitted-c)) and glyphosate ((Hénault-Ethier et al. 2016, Submitted-b)) retention by the RBS.

While the runoff flowpaths obtained based on the regional DEMs suggested heavy flow convergence within the RBS, this was not observed during rainy day field visits. Concentrated flows may be observed in the majority of agricultural RBS, but not in them all (Dosskey et al. 2002). The *field* scale model, which had a lower vertical precision of 1 m and a resolution of 1.5 m, could not be entirely conditioned to calculate the extent of adjunct microbasins (those basins which extend beyond the region encompassed in the proximal model) in BB. Hence, the *proximal* scale, which relied on the dGPS data with 0.01 m vertical and 1 m horizontal precision, and a 50 cm resolution, was judged best for the characterization of surface runoff flowpaths across the RBS, and most of the microbasin surface area calculations described below. At the *proximal* scale, the ephemeral cropland gullies visible may be somewhat more permanent, though not necessarily to the extent of becoming severely eroded classic gullies (Dabney et al. 2006). Runoff flow convergence induces more concentrated surface flows that can overwhelm the RBS capacity (Polyakov et al. 2005; Michaud et al. 2005). These ephemeral gullies are inherent to the topography and may become more permanent, classic gullies under no-till practices (Dabney et al. 2006).

3.3 The influence of scale on agricultural RBS hydrology

Buffer strips may be studied from a multi-scale perspective (Wiens 1989), ranging from laboratory studies, focusing on processes in controlled settings (e.g., Ausland (2014); Gomes et al. (2015)), to watershed or catchment studies (e.g., Smethurst et al. 2009; Ratté-Fortin 2014; Uriarte et al. 2011; Terrado et al. 2014; Dosskey 2001), encompassing or smoothing out local heterogeneities (Wiens 1989; Baker et al. 2001) to make real-life assessments or predictions of overall effectiveness (Figure S2a-c; Norris 1993; Verstraeten et al. 2006; Smethurst et al. 2009; Baker et al. 2001). The current study focused on the intermediate scale, sometimes referred to as field scale (Lee et al. 2003), plot scale (Gasser et al. 2013) or along transects (Munoz-Carpena et al. 1999; Osborne and Kovacic 1993). This scale allows the transverse passage of water and diffuse pollutants through the RBS to be studied (Lee et al. 2004), and is predominant in the literature (Stutter et al. 2012; Dosskey 2001). The current study suggests that even within an intermediate scale, scaling up (i.e., field scale) or down (i.e., focusing solely on the RBS vicinity) may lead to different understanding of surface runoff flowpaths.

3.4 Interception of runoff across the RBS

The spatial variability in surface runoff can be evaluated when considering all the field runoff intercepted by the RBS (Figure 4). There was no significant difference in overall incidence angle (θ; ANOVA by RBS side (i.e., field or stream side of the buffer) or treatment), and although there is local variability in each parcel relative to the perpendicular transects across the buffer strip ($\theta_{\perp}$), there was no significant difference related to side or treatment (testing for ranks on paired data). This means that, overall, the incoming runoff crosses the buffer strip perpendicularly ($\sim 90°$), but at a local scale, incoming (CF) and exiting (CR) surface flows may enter and exit the buffer test parcels at various angles. This is critical for the statistical analysis of RBS potential nutrient (Hénault-Ethier et al. 2016, Submitted-c) and glyphosate (Hénault-Ethier et al. 2016, Submitted-b) retention effectiveness.

3.5 Size of microbasins draining towards the RBS

On average, microbasins were smaller in BB than in SR ($p < 0.0001$* for both ‘’basins’’ and ‘’closest streams’’ models; Table S1 and Figure S4). Although the ‘’stream’’ model did not reveal different surface areas between treatments ($p = 0.3897$), the ‘’closest stream’’ model revealed that the area drained was statistically larger for the RBS composed of 5 rows of willows (5X), than for the RBS with 3 rows of willows (3X). The herbaceous treatment (CX) was statistically indistinguishable from both willow treatments ($p = 0.0073$*), and there was a significant interaction between treatment and site ($p = 0.0102$*). While calculations based on the drainage points superimposed on the rock chute (a common erosion protection structure found at the edges of fields) in SR yielded similar results (CX = 5X ≥ 3X; $p = 0.0009$*), affiliated basins in BB were statistically larger in 3X and smaller in 5X (CX indistinguishable; $p = 0.0408$*). Although the surface collectors were not installed specifically where the hydrological model suggests concentrated runoff, because the model was built only after the installation of the sampling equipment, the surface runoff collectors were nevertheless effective in intercepting the water that flowed through.

A single method for calculating microbasins may not be broadly applicable. For instance, the affiliated basins model, which enabled the calculation of the area draining into the RBS using the field model’s less precise data in a few areas where the proximal model was too narrow to fully capture the whole surface area of the microbasin, was only applicable in BB, and drainage points on rock at the nearest chutes, engineered erosion control systems in place, could only be positioned in SR. Finally, some automatically generated hydrological microbasins may be relatively small (1-72 % smaller) compared to what would be expected if the closest modeled runoff path effectively intercepted the collector. However, there was not always a runoff stream located in the realistic vicinity of the runoff collector, and hence, three SR parcels could not be attributed a surface area under the ''closest stream'' model. This inherently limits the subsequent use of these modeled data to interpret the potential effectiveness of the RBS to filter aqueous fluxes of nutrients and glyphosate.

3.6 Runoff volumes intercepted and the effect of source area

Because of between-site differences in topography, stratigraphy, microbasin sizes, and K_{sat}, runoff volumes were analyzed independently for each site. The 2011 runoff volumes (recorded on eight occasions; Figure 5) were unaffected by RBS side ($p = 0.7204$) and treatment ($p = 0.3320$) in BB. However, the RBS significantly reduced runoff volumes in SR (side: $p = 0.0110$*), even though it remained unaffected by treatment ($p = 0.7005$). Except for a very weak, although significant relationship between runoff volume collected from the edge-of-field and microbasins size obtained from the ''closest stream'' model in BB ($r^2 = 0.10$, $p < 0.0001$*, $n = 162$; Figure 6), no other significant relationships were found between runoff volumes and slopes of microbasins size models (data not shown). Runoff volume was not linearly related to any source area measurement model, except in BB, where the ''nearest stream'' microbasin model was significantly and linearly related to collected runoff volume.

Several other studies found a direct relationship between runoff volume and source area (Herron and Hairsine 1998; Dosskey et al. 2002; Polyakov et al. 2005). Two explanations may underlie the absence of such a relationship in this experiment. First, experiments under uncontrolled field conditions, where surface water flow is not restricted by partitions between parcels or via the interception of all runoff and infiltrated water with transverse ditches, will lead to more variable water capture. This may eventually affect how potential RBS effectiveness is interpreted between uncontrolled versus controlled conditions. For instance, the effective area of an RBS, through which water actually flows, may be only a fraction of the total RBS area (i.e., the entire vegetated surface adjacent to the stream), especially if concentrated runoff occurs (Dosskey et al. 2002). Secondly, although various models to calculate source area (i.e., the size of the microbasin draining toward the RBS or water samplers) were tested, based on the most precise and relevant scales, these estimates remain strongly dependent on the accuracy of the dGPS measurements and constructed topographic models. Hence, it cannot be ruled out that the lack of predictive power for runoff volume collection based on source surface area could be due to model assumptions. Assuming that the whole (gross) RBS area (54 m^2) contributed to runoff interception, our source area to RBS area ratio varied from 0 - 17.8 based on the ‘’closest stream’’ model. However, if we only consider the 60 cm gutter as effectively intercepting runoff which flows across the 3 m width RBS (effective area of 1.8 m), then our source- to RBS-area ratio (effective area) varies between 0 and 958. The majority of previous studies that varied the source-:RBS-area ratio in a controlled manner (range 5:1 – 45:1) found that the ratio did not significantly influence the potential RBS effectiveness, because of variability in the infiltration rates across studies (Krutz et al. 2005). In RBS of uniform width, some zones with a larger source-area (Herron and Hairsine 1998; Dosskey et al. 2002; Polyakov et al. 2005) due to converging flow paths end up insufficiently protected (Dosskey et al. 2002; Polyakov et al. 2005), arguing in favor of precision RBS with varying width, optimized for actual terrain characteristics (Polyakov et al. 2005). Therefore, it was hoped that studying this ratio within an apparently uniform field where the source area varies naturally due to topography would control for the across-site variability of earlier studies, and allow for better discernment of the source area effect, but was not found to be the case. In this study, source area, or microbasins, draining toward the RBS or water samplers were taken into account to address the fact that some of the water from the larger field watersheds (~10.1 ha in BB and ~8.3 ha in SR) was draining toward ditches rather than toward the RBS.

3.7 Implications of spatiotemporal hydrologic flux heterogeneity in the evaluation of potential RBS effectiveness in nutrient and glyphosate retention

The common assumption that most runoff reaches a buffer, enters the buffer, and flows through it perpendicularly, except for a portion that infiltrates, appears erroneous, based on our observations and previous ones of Dabney and Vieira (2013). It has been demonstrated here that over the proximal or field scales, modeled runoff incidence does enter and exit the RBS at a near perpendicular angle. However, within each parcel the runoff incidence angle deviates widely from the expected perpendicular flow. This appears critical to truly appreciating the potential effectiveness of the RBS presented in two earlier articles on nutrients (Hénault-Ethier et al. 2016, Submitted-c) and on glyphosate (Hénault-Ethier et al. 2016, Submitted-b).

The observations made in the current work suggest a specific potential effectiveness calculation to avoid the confounding effect of local heterogeneities. The movement of surface water in the field influences the ability to collect runoff in the surface sampling equipment. This is especially critical at a local scale, where sampling equipment in front of the buffer strip may receive more or less water than the equipment on the other side of the buffer, due to local topography/hydrology and not to specific buffer strip treatments. However, because the mean incidence angle is perpendicular to the buffer strips at the regional field scale, pooling data from in front of the buffer strip should minimize the confounding effects of local heterogeneities. Pairing proximal stations before and after the buffer strip, as was initially intended in field data collection design, did not appear pertinent after analyzing the modeled trajectory of the surface runoff. Therefore, scaling up to analyze mean pollutant loads in front of and behind the buffer strip should minimize concentration variability, which would have otherwise been exaggerated in a paired statistical design.

3.8 Paired or unpaired statistical designs

RBS effectiveness is commonly calculated as the difference between inflowing and outflowing volumes or concentrations, expressed as a percentage of the inflow value (McKergow et al. 2006; Sabater et al. 2003; Hook 2003). This formula is sometimes normalized per meter width of RBS to allow for inter-site comparisons (Sabater et al. 2003). When partitioned runoff plots are used (Dosskey et al. 2007; Patty et al. 1997; Duchemin and Hogue 2009; Schmitt et al. 1999), sheets of metal physically separate the parcels and all the runoff from the source area (minus any infiltrated water) is assumed to be intercepted by the RBS. In hydrologically isolated experimental plots, paired statistical designs, where RBS inputs are considered as a ratio of RBS outputs for each parcel, make sense, as the water must flow across the RBS, within the hydrological boundaries used in the experimental setup. However, no hydrological partitions between parcels were used in this experiment (i.e., an uncontrolled setup was instead implemented).

RBS pollutant removal effectiveness is also often measured in a way which appears more akin to an unpaired statistical design, by measuring pollutant loads in the presence versus in the absence of an RBS, in parallel as opposed to linear plots (Lee et al. 2003; Munoz-Carpena et al. 1999; Noij et al. 2012; Uusi-Kämppä and Yläranta 1996; Duchemin and Hogue 2009).

Where surrogate runoff is applied (Dosskey et al. 2007; Schmitt et al. 1999), RBS input concentrations can be estimated from the tank mix. However, in uncontrolled settings with natural rainfall, the inflow and outflow concentrations may not be homogeneous. It is therefore suggested that averaging edge-of-field or inflow concentrations over the whole field region may compensate for small-scale heterogeneity leading to unrepresentatively high or low concentrations in the inflow, which does not necessarily migrate from the field to the stream perpendicularly to the RBS. This is somewhat similar to the approach of McKergow et al. (2006), who reported aggregate concentrations and loads rather than individual plot values, so as to minimize the spatial variability among multiple RBS plots. Unlike the current work, however, McKergow et al. (2006) used a paired statistical design. Therefore, to interpret RBS efficiency in uncontrolled field plots, it appears best to average inflowing and outflowing concentrations at the field scale, rather than using a statistical design based solely on geographic proximity pairing (i.e., linear plot paired design). This justified the statistical approach used to measure the RBS effectiveness in mitigating nutrient and glyphosate runoff (Hénault-Ethier et al. 2016, Submitted-b; Hénault-Ethier et al. 2016, Submitted-c).

3.9 Groundwater flow and water table height

Though surface soil appeared to be homogeneous at both sites, below surface soil strata varied slightly between parcels. A total of nine soil types were observed across both sites (see Figure S5 for 3D stratigraphic rendering). In BB, black histosol, brown histosol, peat, marl, rocks (till), and clay were observed from the surface to the core bottom. In SR, sandy loam, clean sand lentils, and clay with traces of iron oxides (FeOX) were observed from top to bottom. While black, brown histosol, and peat are mapped differently, they represent arbitrary stages on a continuum of organic soil pedogenesis, with black histosol being the most humified form. Therefore, apparent changes between stratigraphic layers in 3D representation represent a transition of peat oxidation stage rather than abrupt physico-chemical changes. On the other hand, rocks (likely washed till) found near the F-F', E-E' and to a lesser extent east of the C-C' transects, may have more important impacts on groundwater movement, which may be explained by the historic position of the stream (Figure S1). Organic-rich soil generally surrounds the 30 cm lysimeters, while marl and/or clay surrounds the 70 cm lysimeters.

As expected, groundwater levels are higher in the spring than in the summer months (Figure 7). Our observations suggest groundwater-surface water connectivity at BB, visible through a resurgence zone in the eastern region of the study area. Groundwater generally moves from the fields to the streams, except for in driest periods in BB, although, again, not necessarily at an angle perpendicular to the RBS. During periods of snowmelt in SR, water in the saturated soils did not appear to flow in half of the sampling zones, as demonstrated by the lack of a gradient from the CF to CR sides. Furthermore, the variability of groundwater flow may be influenced by stratigraphy and localized soil physico-chemistry (Figure S5), as well as historical modifications of agricultural stream beds (Figure S1).Spatiotemporal heterogeneity of the groundwater flow therefore needs to be taken into consideration in the interpretation of potential RBS effectiveness in removing nutrients ((Hénault-Ethier et al. 2016, Submitted-c)) and glyphosate (Hénault-Ethier et al. 2016, Submitted-b).

3.10 Implications of spatiotemporal groundwater heterogeneity in the evaluation of potential RBS effectiveness in nutrient and glyphosate retention

In humid climates, where aquifers are connected to rivers, groundwater generally flows laterally towards streams (Winter et al. 1998). Although some substrates permit faster water movement, groundwater flow is generally slower than surface runoff (Winter et al. 1998; Dosskey et al. 2010). As different soil layers with different hydraulic properties can dictate how the water migrates horizontally and vertically, this in turn influences pollutant residence time, interaction with the root zone, interaction with organic-rich or microbiologically-active horizons, and subsurface leaching, which all affect the effectiveness of the RBS in mitigating underground diffuse pollution (Polyakov et al. 2005). For instance, a high water table alone is not sufficient to predict denitrification in a RBS (Vidon and Hill 2004), but pairing with elevated dissolved organic carbon measurements improves denitrification prediction potential in microanaerobic hot spots (Burt et al. 1999; Hill 1996; Pabich et al. 2001). Groundwater sometimes seeps to the surface, leading to rapid flow across the RBS that does not allow for effective water treatment (Bentrup 2008). Alternately, for deeply incised streams, groundwater may be too deep for the RBS vegetation to significantly intercept it (Bentrup 2008). To correctly assess the effectiveness of an RBS, historic land disturbances, restricting soil layers, preferential groundwater flow paths, and other features that control diffusion and infiltration of dissolved or particulate aqueous pollutants should be considered (Polyakov et al. 2005). From this study, it appears important to adequately assess groundwater flow direction and depth in the evaluation of RBS effectiveness in filtering nutrient and glyphosate. Contrary to statistical assumptions in the calculation of RBS effectiveness, relying on RBS inputs versus outputs, the groundwater flow reversal observed in the low water table summer months at BB, where the stream was connected to groundwater, may have affected the perceived ineffectiveness of the RBS.

Bank storage (i.e., underground flow from stream to field) may also occur due to temporary flood peaks or intense evapotranspiration by streamside vegetation (Winter et al. 1998). When the water table below the fields and RBS is low due to low precipitation or intense evapotranspiration, an underground source emerging from a confined aquifer or an intense precipitation pulse may lead to flow reversal. This was taken into account in earlier studies on potential RBS effectiveness (Hénault-Ethier et al. 2016, Submitted-b; Hénault-Ethier et al. 2016, Submitted-c). Furthermore, historical straightening of streams may alter the normal hydrogeology, such that groundwater may continue to flow in its natural course if the substrate is more conductive there, despite what is apparent from the aboveground superficial modifications of the stream bed (see Figure S1). As preferential groundwater flow channels may cause the observed subaqueous springs (Winter et al. 1998), this is a plausible explanation for the groundwater flow reversal post-glyphosate application in BB.

4. Conclusions

The objective of this study was to explore whether surface and groundwater hydrology could explain the limited effectiveness of narrow RBS in mitigating the nutrient and pesticide runoff witnessed in previous studies. It appears critical to always assess whether water flows across the RBS in such a way that vegetation can intercept surface runoff and groundwater. The assumption that water flows from the fields to the streams in a nearly perpendicular fashion was not confirmed everywhere. However, when averaging all runoff streams at the proximal field scale, the runoff streams generally appear to cross the RBS perpendicularly. Therefore, pooling the results of localized water samples used to quantify agro-chemical concentrations may help to buffer the small-scale heterogeneity of surface runoff. Furthermore, the *a priori* assumption that a larger source area (microbasin) would lead to greater surface runoff volumes crossing the RBS at any given point was not confirmed. We nevertheless caution the use of microbasin area estimates in uncontrolled field studies, using various estimation methodologies to constrain inherent inter-site heterogeneities in uncontrolled fields. The current study suggests that even at an intermediate scale, scaling up (field scale) or down (immediate RBS vicinity) may alter our understanding of surface runoff flowpaths, which may in turn have potential implications for the calculation of perceived RBS effectiveness in mitigating non-point source pollution.

Below surface runoff, phreatic waters may also deviate from the implicit assumption that water should flow from field to stream. Phreatic waters may indeed flow from field to stream in a nearly perpendicular fashion most of the time. However, soil saturation in the spring may lead to subtle horizontal water movement, heterogeneous soil stratigraphy may lead to flows that are not necessarily perpendicular to the RBS, and connectivity with regional aquifers may lead to water flowing from the stream to the field in the driest summer months. Consideration of groundwater flow direction thus appears to be critical to any evaluation of RBS effectiveness.

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Table 1: Granulometry and saturated hydraulic conductivity (K_{sat}) at Boisbriand and Saint-Roch-de-l'Achigan.

			Boisbriand			Saint-Roch-de-l'Achigan		
Parameter	Depth (cm)	Coarse sand < 2 mm	Fine sand < 212 µm	Silt and Clay <63 µm		Coarse sand < 2 mm	Fine sand < 212 µm	Silt and Clay <63 µm
Granulometry[1]	0	6.1	13.3	80.5		43.2	30.1	26.7
	35	6.4	13.9	79.7		37.2	33.3	29.4
Soil series		CF	Dalhousie[3]	Châteauguay[3]	Saint-Bernard[3]	Achigan[3]	Achigan[4]	
K_{sat} (cm/h)	0-10	0.03 to 4.02[2]	N/D[3]	N/D[3]	N/D[3]	N/D[3]	N/D[4]	
	0-30	N/D	0.53[3]	4.00[3]	8.00[3]	0.61[3]	1.30[4]	
	30-40	N/D	0.12[3]	2.33[3]	4.28[3]	1.50[3]	1.31[4]	
	>40	N/D	0.47[3]	2.00[3]	N/D[3]	N/D[3]	N/D[4]	

Notes: [1] Granulometry was obtained by sifting across indicated diameter mesh, and a proportion of silt of 72.2% and 76.7% was observed, in Boisbriand and Saint-Roch-de-l'Achigan respectively, in the smallest fraction using a sedigraph. [2] K_{sat} was measured in Boisbriand using a Guelph Permeameter, on the field-edge (CF) of the riparian buffer strip. Other K_{sat} values were obtained by soil series from the litterature [3]Gagné et al. (2013), [4]MAPAQ (1990).

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Montréal, October 12th 2016

Object: Publication submission to Journal of Hydrology - **Hydrological Heterogeneity in Agricultural Riparian Buffer Strips**

Dear editor,

Our team is pleased to submit an original research paper on runoff and groundwater spatio-temporal heterogeneity which may impact the effectiveness of grassy or shrub willow buffer strips against nutrients or pesticides runoff from fields, for consideration as an original research article in *the Journal of Hydrology*. This publication concerns how we may measure the effectiveness of narrow riparian buffer strips which are mandatory in several regions of the world.It covers aspects of surface hydrology (runoff) and groundwater hydrology, attempting to interpret how spatio-temporal heterogeneities may affect the way riparian buffer strips effectiveness is calculated based on pollutant concentrations before or after vegetated buffer strips..

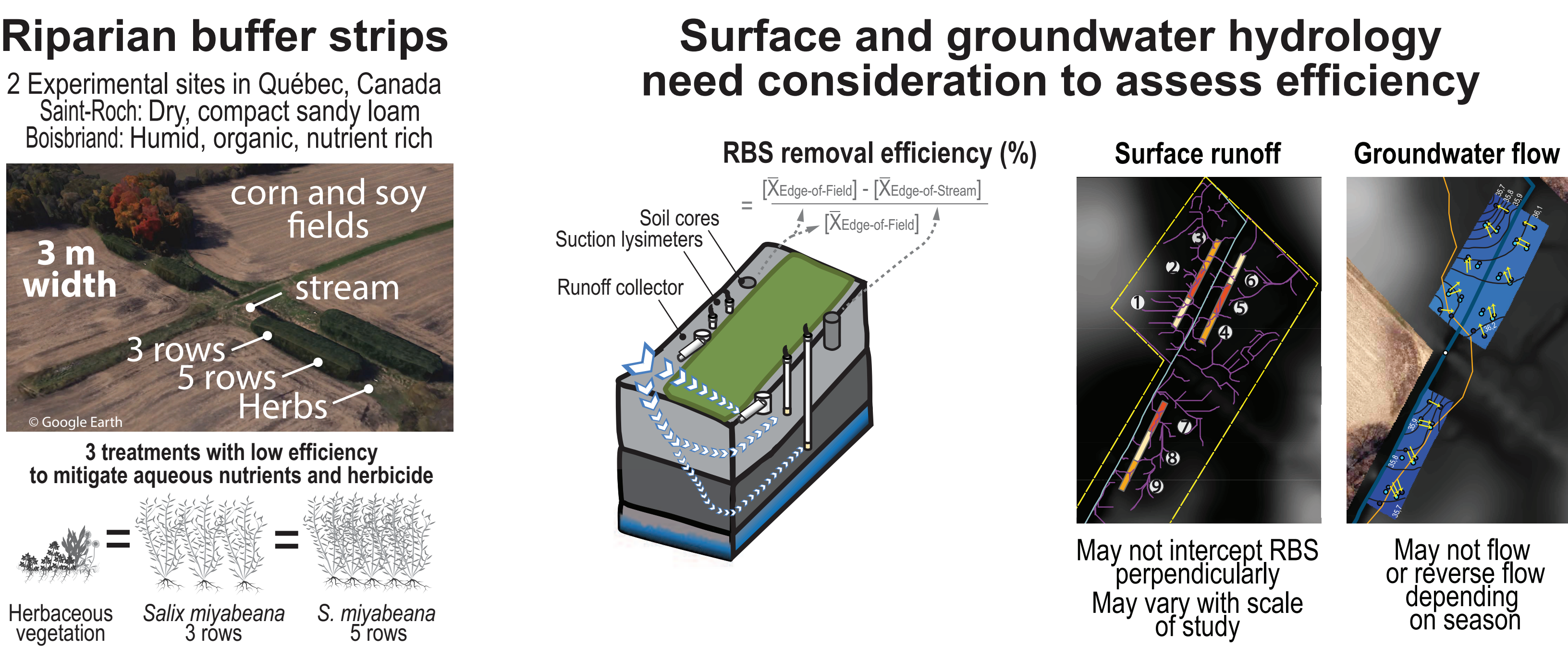
While riparian buffer strips in agricultural settings have been studied for decades, our paper involves a novel vegetation design and improved methodologies. We tested the potential efficiency of fast growing willows which could generate energetic biomass for the farmers. Instead of trying to increase the buffer strip efficiency by widening it, like several other studies have done in the past, we tested the possibility of increasing its efficiency by establishing a denser plantation. In addition, many studies rely on controls that have little to do with actual agricultural practices (i.e. bare soil, cultivated grass, intensive maintenance, etc.), here we focused on ruderal vegetation spontaneously colonizing riparian areas, using the minimal maintenance that a farmer would most likely practice (mowing once a year). Our study attempts to sensitize riparian buffer scientists to the importance of correctly assessing surface and groundwater flow direction when calculating effectiveness to remove non-point source pollution. While several riparian buffer strip studies are conducted in hydrologically disturbed or controlled experimental parcels (partitions, trenches, artificial runoff or rain, etc.), our experimental design was intended to best depict natural hydrological heterogeneities.

Depicting *real life* settings was essential for the current study, which aimed at testing a governmental policy in place in the province of Québec (Canada). Though our story takes place in Québec, Canada, the current research results are highly interesting to an international audience as farmers across the world need to dedicate efforts to water protection and because many jurisdictions settled on narrow buffer strips as a compromise between farmers losses of revenues and environmental protection, our biomass producing narrow buffer design represents an interesting approach.

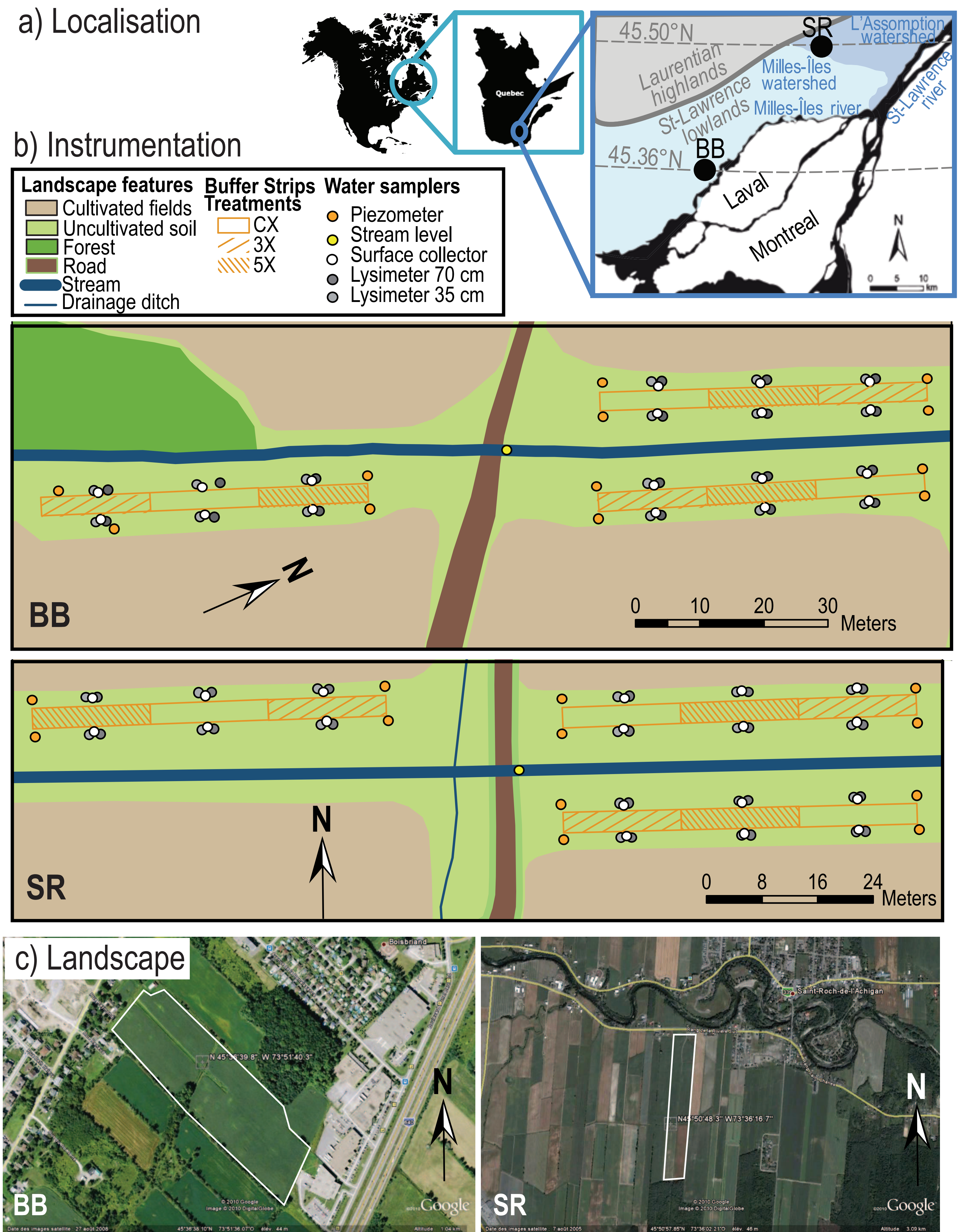
Thank you for the consideration given to the current manuscript,

Louise Hénault-Ethier, PhD
Institut des Sciences de l'Environnement
Université du Québec à Montréal
Louisehenaultethier@hotmail.com
514-713-6839

Graphical Abstract (for review)



Figure



a) Localisation
Quebec
45.50°N
45.36°N
SR
BB
L'Assomption watershed
Laurentian highlands
Milles-Îles watershed
St-Lawrence lowlands
Milles-Îles river
St-Lawrence river
Laval
Montreal
N
0 5 10 km
b) Instrumentation
Landscape features
Cultivated fields
Uncultivated soil
Forest
Road
Stream
Drainage ditch
Buffer Strips Treatments
CX
3X
5X
Water samplers
Piezometer
Stream level
Surface collector
Lysimeter 70 cm
Lysimeter 35 cm
BB
N
0 10 20 30 Meters
SR
N
0 8 16 24 Meters
c) Landscape
Boisbriand
N 45°35'39.8" W 73°51'40.3"
N
BB
Google
Saint-Roch-de-l'Achigan
N45°50'48.3" W73°36'16.7"
N
SR
Google

Figure 2

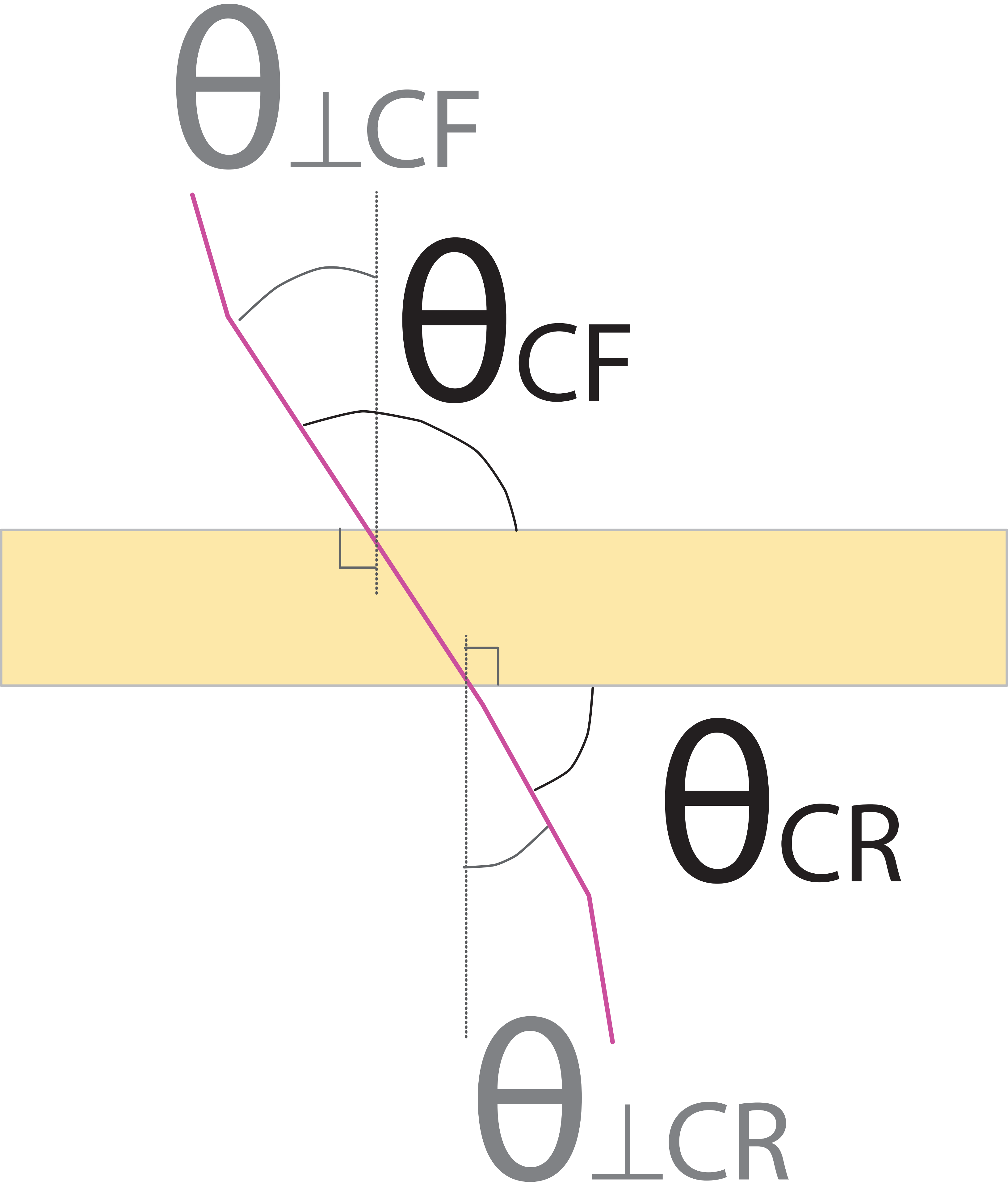
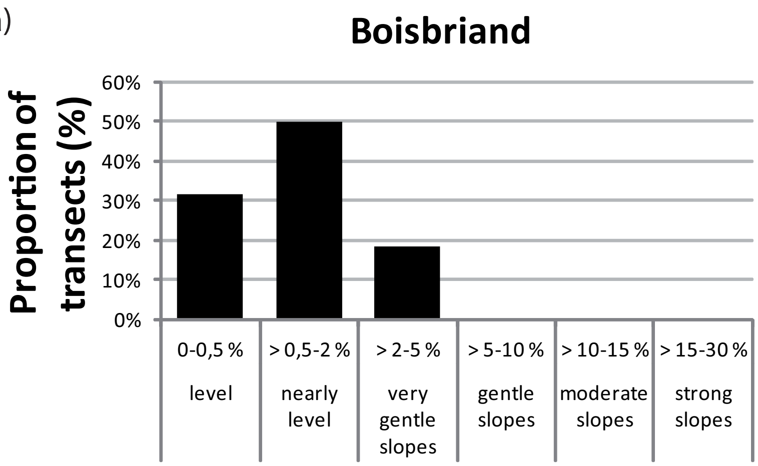


Figure 3

a)


Boisbriand
Proportion of transects (%)
60%
50%
40%
30%
20%
10%
0%
0-0,5 %
level
> 0,5-2 %
nearly level
> 2-5 %
very gentle slopes
> 5-10 %
gentle slopes
> 10-15 %
moderate slopes
> 15-30 %
strong slopes

b)

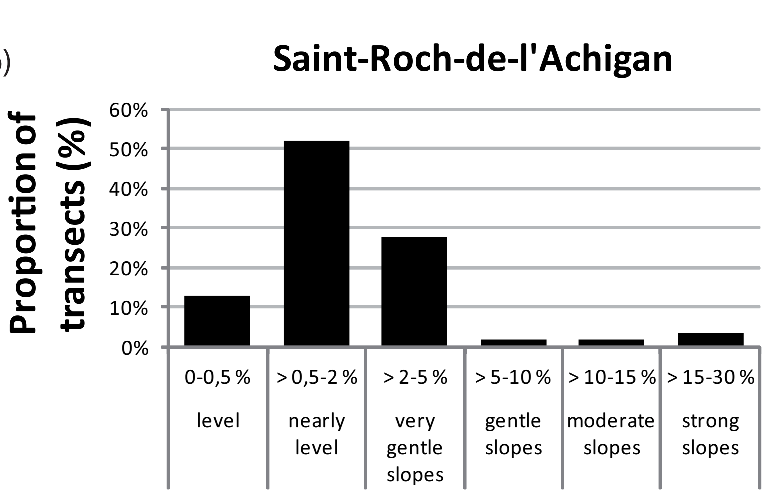
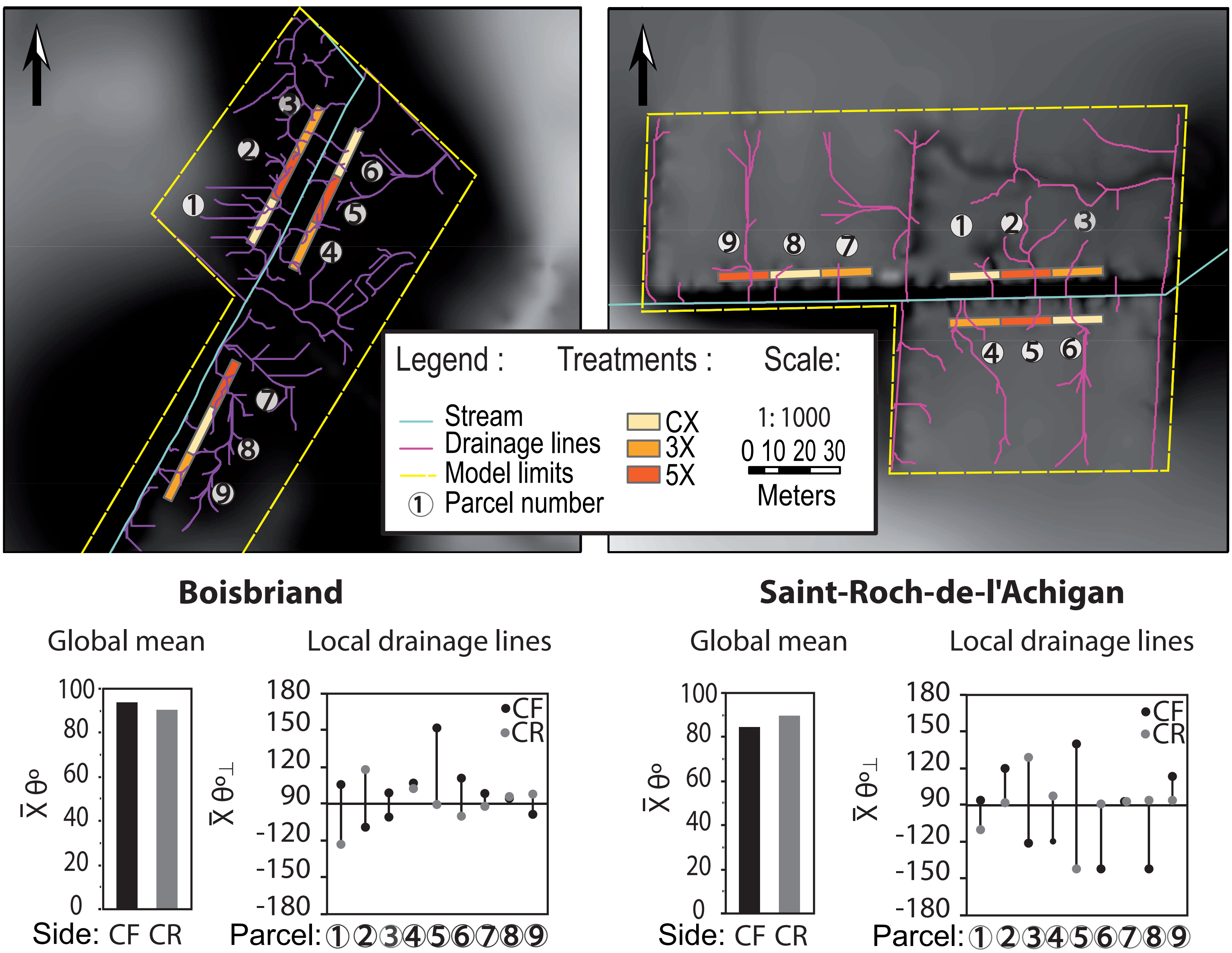
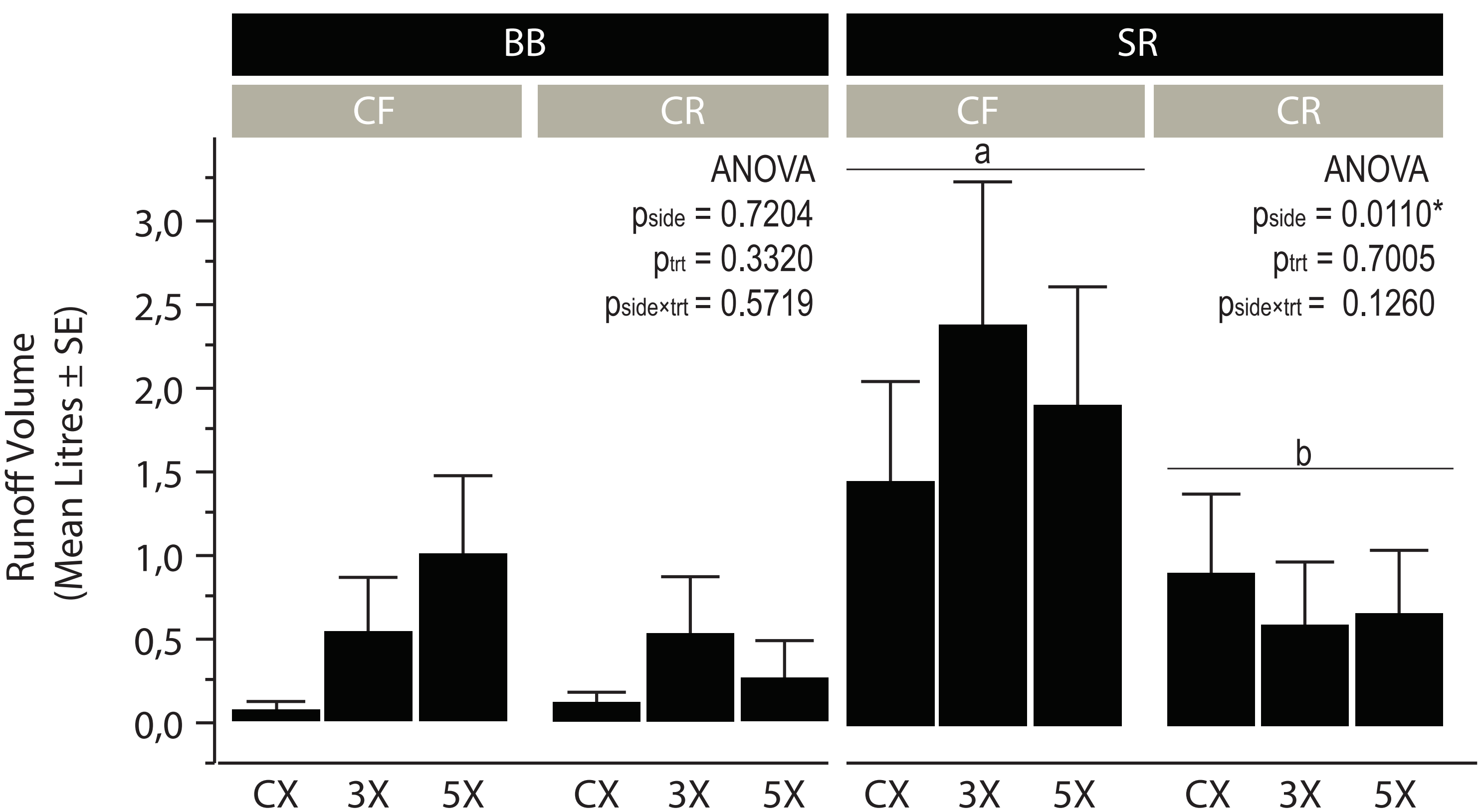

Saint-Roch-de-l'Achigan
Proportion of transects (%)
60%
50%
40%
30%
20%
10%
0%
0-0,5 %
level
> 0,5-2 %
nearly level
> 2-5 %
very gentle slopes
> 5-10 %
gentle slopes
> 10-15 %
moderate slopes
> 15-30 %
strong slopes

Figure 4



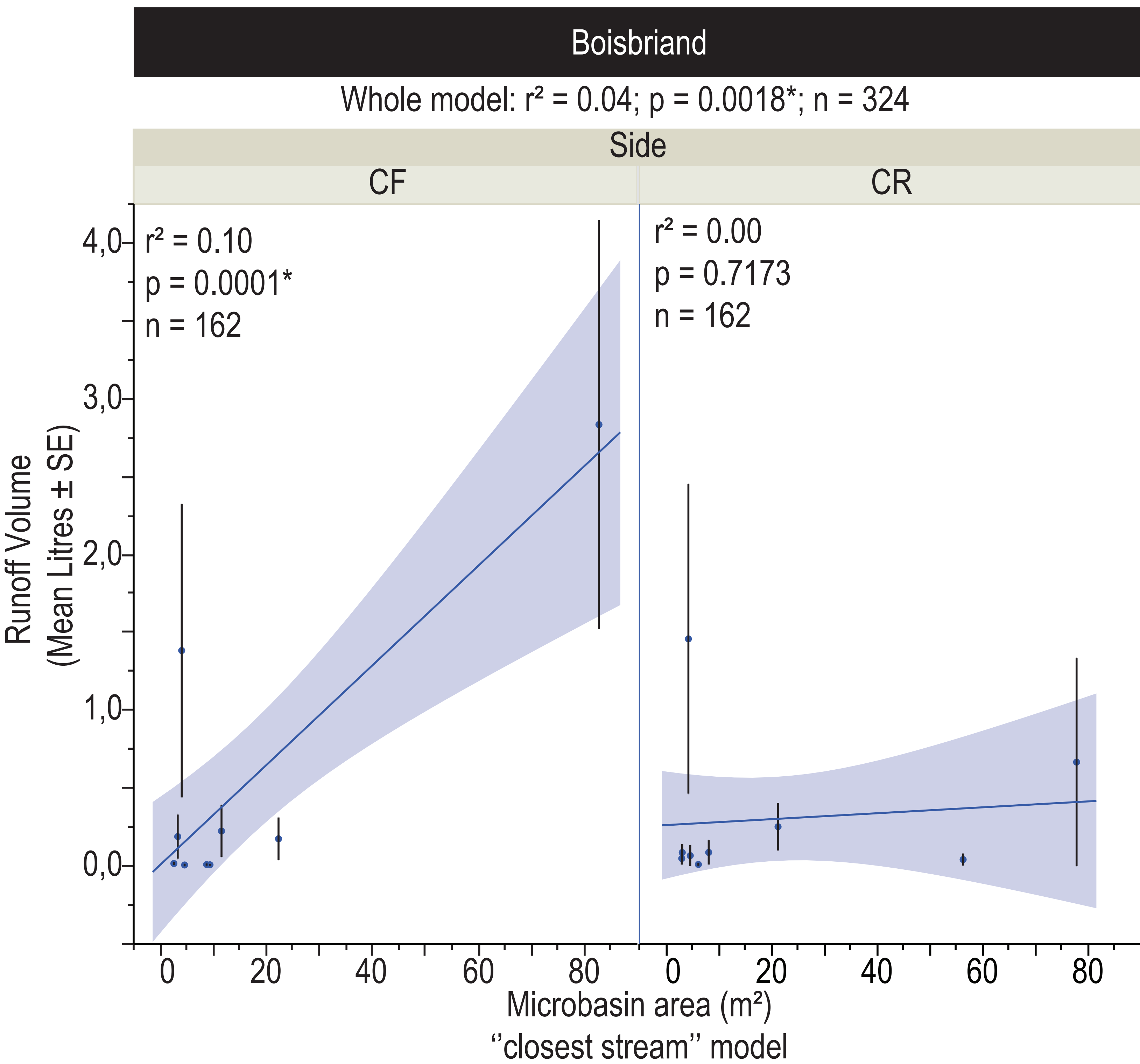
Legend :
Stream
Drainage lines
Model limits
Parcel number
Treatments :
CX
3X
5X
Scale:
1: 1000
0 10 20 30
Meters
Boisbriand
Saint-Roch-de-l'Achigan
Global mean
Local drainage lines
CF
CR
Side: CF CR
Parcel: ① ② ③ ④ ⑤ ⑥ ⑦ ⑧ ⑨

Figure 5



BB
SR
CF
CR
CF
CR
ANOVA
p side = 0.7204
p trt = 0.3320
p side×trt = 0.5719
a
ANOVA
p side = 0.0110*
p trt = 0.7005
p side×trt = 0.1260
b
Runoff Volume
(Mean Litres ± SE)
3,0
2,5
2,0
1,5
1,0
0,5
0,0
CX
3X
5X
CX
3X
5X
CX
3X
5X
CX
3X
5X

Figure 6



Boisbriand
Whole model: r² = 0.04; p = 0.0018*; n = 324
Side
CF
CR
r² = 0.10
p = 0.0001*
n = 162
r² = 0.00
p = 0.7173
n = 162
4,0
3,0
2,0
1,0
0,0
0
20
40
60
80
0
20
40
60
80
Runoff Volume
(Mean Litres ± SE)
Microbasin area (m²)
''closest stream'' model

Figure 7a

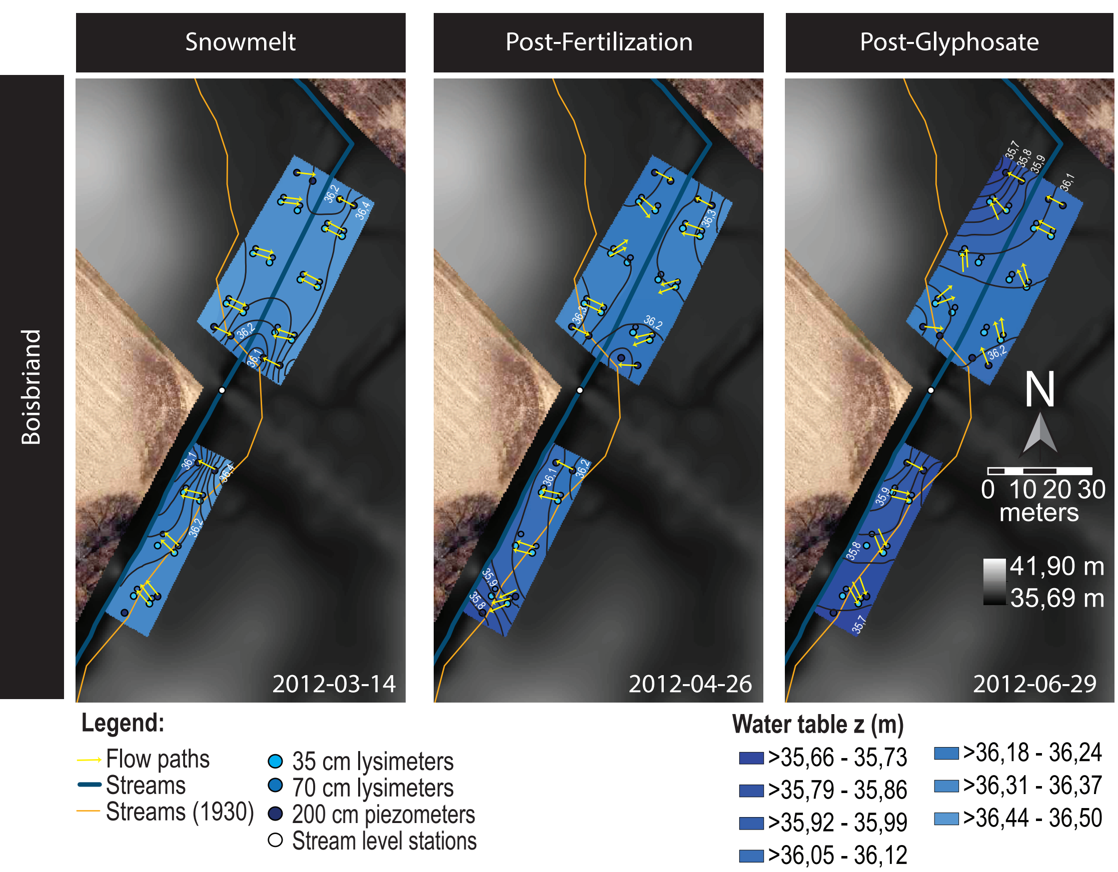
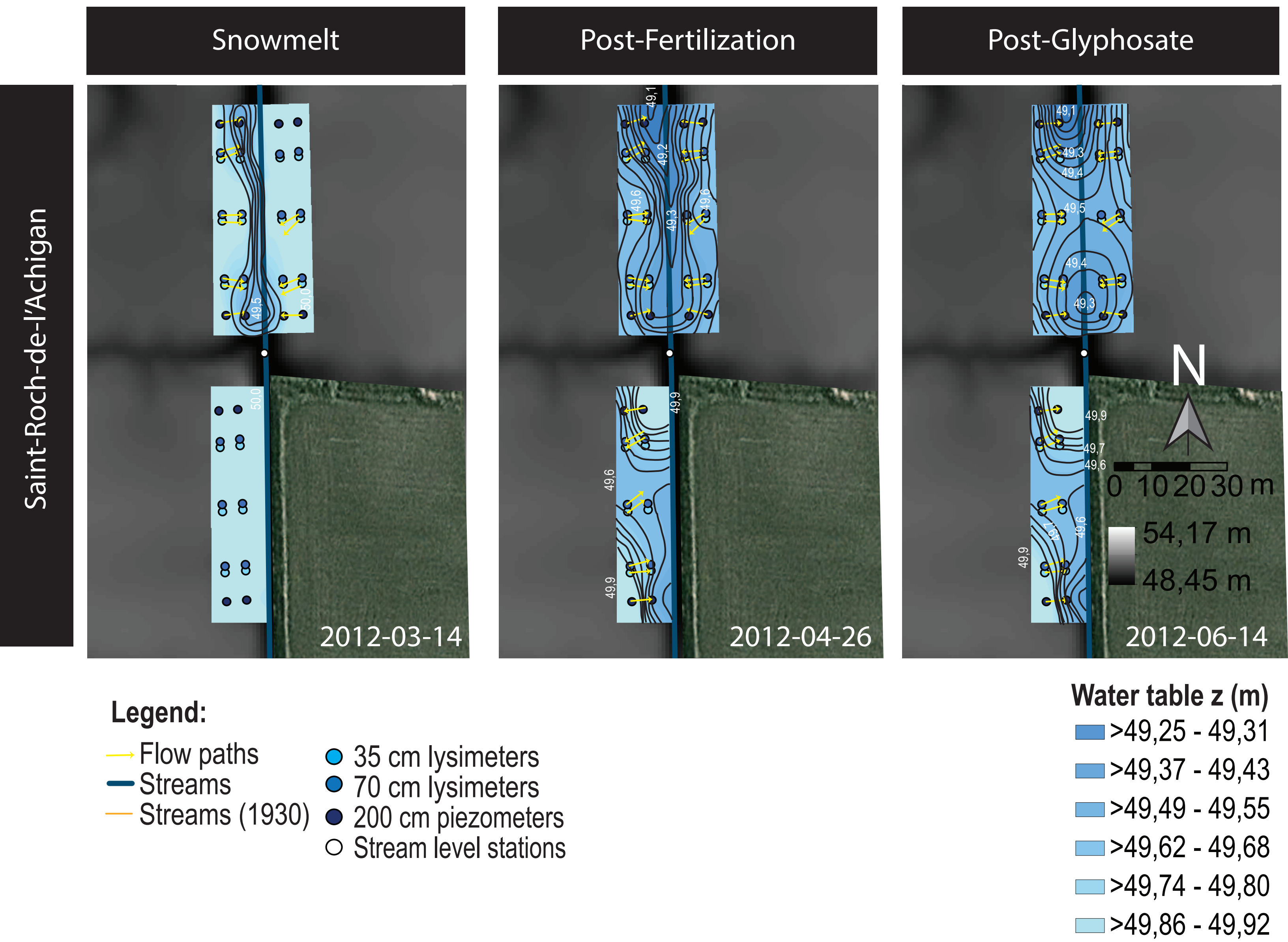

Snowmelt
Post-Fertilization
Post-Glyphosate
Boisbriand
2012-03-14
2012-04-26
2012-06-29
N
0 10 20 30
meters
41,90 m
35,69 m
Legend:
Flow paths
Streams
Streams (1930)
35 cm lysimeters
70 cm lysimeters
200 cm piezometers
Stream level stations
Water table z (m)
>35,66 - 35,73
>35,79 - 35,86
>35,92 - 35,99
>36,05 - 36,12
>36,18 - 36,24
>36,31 - 36,37
>36,44 - 36,50

Figure 7b



Snowmelt
Post-Fertilization
Post-Glyphosate
Saint-Roch-de-l'Achigan
2012-03-14
2012-04-26
2012-06-14
N
0 10 20 30 m
54,17 m
48,45 m
Legend:
Flow paths
Streams
Streams (1930)
35 cm lysimeters
70 cm lysimeters
200 cm piezometers
Stream level stations
Water table z (m)
>49,25 - 49,31
>49,37 - 49,43
>49,49 - 49,55
>49,62 - 49,68
>49,74 - 49,80
>49,86 - 49,92

Supplementary Figure S1

Click here to download Supplementary material for on-line publication only: Figure S1 Photo_aerienneBB_1930 vs 2013_1-3000_

Supplementary Figure S2

Click here to download Supplementary material for on-line publication only: Figure S2 RBS scales diagram.eps

Supplementary Figure S3

Supplementary Figure S4

Supplementary Figure S5

Illustration captions

Figure 1: (a) Location maps, (b) water sampling equipment of the Boisbriand (BB; left) and Saint-Roch-de-l'Achigan (SR; right) sites in Quebec, Canada. (c) Satellite images showing the landscape. The stream flows south-west in BB and east in SR.

Figure 2: Methodology for calculating the incidence angle of incoming runoff on the edge of field (CF) and the edge of stream (CR).

Mean angle relative to buffer strip for all drainage lines is marked as θ_{side}. Mean deviation from perpendicular for local drainage lines ($\theta\perp_{side}$).The CF or CR RBS edges were used to calculate the angle of incidence (θ) or the angle relative to a perpendicular flow line crossing the buffer strip $\theta_{\perp}$

Figure 3: Distribution of slopes for (a) Boisbriand and (b) Saint-Roch-de-l'Achigan.

For each site, 54 transects (4 m) were measured for slope both across the buffer strip and just before the buffer strip. Slopes greater than 5% at Saint-Roch-de-l'Achigan suggest preferential runoff flow paths (scale 1:1000).

Figure 4: Surface runoff incidence angle in Boisbriand and Saint-Roch-de-l'Achigan based on the proximal field scale drainage lines.No significant difference in runoff incidence angle for side (CF vs CR), treatment (CX, 3X, 5X), geographic quadrant (NE, SE, SW) or site (BB, SR) for mean θ but $\theta\perp$ varies for each parcel. There was no significant difference (ANOVA) between side and treatment on the overall runoff incidence angle (θ) (histograms), and though there is local variability in each parcel relative to the perpendicular transects across the buffer strip ($\theta_{\perp}$)(needle diagram), there was no significant difference which could be linked with side or treatment (testing for ranks on paired data). This means that globally, the incoming runoff crosses the buffer strip in a perpendicular fashion (~ 90°), but on a local scale incoming (CF) and exiting (CR) preferential surface flows may enter and exit the buffer test parcels at variable angles.

Figure 5: Average runoff volume collected in 2011 on two sites (BB vs SR), two sides (CF vs CR) and three treatments (CX, 3X, 5X).

Figure 6: Average runoff collected in 2011 in Boisbriand, before (CF) or after (CR) the buffer strip, in relation to the size of the source microbasin area calculated from the "closest stream" model.

Figure 7: (a) Boisbriand: Water table altitude (blue scale) during characteristic agricultural sampling periods within the contextual field surface elevation (black and white scale).

The water table is highest at snowmelt on both sites, and lowest post-glyphosate. Amplitude of the phreatic water table vertical movement is approximately 85 cm in BB and 75cm in SR from the spring to summer. In BB, spring water table flows towards the stream, and resurgence zones were observed east of the stream water level station. In dryer months, there is a reversal of groundwater flows and the stream appears to feed the phreatic water table with water flowing towards the north for the eastern parcels and flowing towards the east in the south-western parcels. In these moments, water seems to deviate from the current stream position, perhaps under the geological influence of the stream bed prior to linearization (1930). In SR, the groundwater appears disconnected from the stream, and no flow reversal occur in the dryer months. Furthermore, note that the ground appears totally saturated with water in the spring and no flow direction could be discerned in half of the stations based on water table altitude isobars (water assumed to flow perpendicularly to them).

Figure 7: (b) Saint-Roch-de-l'Achigan: Water table altitude (blue scale) during characteristic agricultural sampling periods within the contextual field surface elevation (black and white scale).

Figure S1: Important landmarks in Boisbriand during the experimental time versus their historical positioning in 1930.

Figure S2: RBS scales and sub-scales.

Figure S3: Drainage lines in Boisbriand (left) and Saint-Roch-de-l'Achigan (right) at three different scales: RBS (green), proximal (purple) and regional or field scale (blue). Drainage lines nearly overlap at the three scales, though smaller unconnected lines are visible at the RBS scale and only major drainage lines are visible at the field scale. For further analysis, only the proximal scale is used.

Figure S4: Drainage basin surface area models schematic representations. (1) Basins (Catchment) in light blue; (2) Nearest stream (drainage points is black dot placed on closest drainage line); (3) Affiliated basins (BB Only, CF in dark blue and CR in light blue) and (4) Drainage points to nearest rock chute (SR Only, small black dots). Figures are presented side by side to avoid overcrowding of information.

Figure S5: Three dimensional stratigraphic models of Boisbriand (top) and Saint-Roch-de-l'Achigan (bottom).

Transects G-G' and J-J' are located on the edge-of-field; transects H-H' and I-I' are located on the edge-of-stream, and both sets of transects are separated by 3 m. Transects A-A', B-B' and C-C'; as well as D-D', E-E' and F-F' are separated by 17 m and are located at mid-point of each riparian buffer treatment parcels. The 0, 35 and 70 cm water sampling equipment is situated near the intersection of perpendicular transects. Note that depth (Z axis) is magnified by a factor of 10X to facilitate discernment of stratigraphic layers.