



Biomass carbon, nitrogen and phosphorus stocks in hybrid poplar buffers, herbaceous buffers and natural woodlots in the riparian zone on agricultural land



Julien Fortier ^{a, b, *}, Benoit Truax ^a, Daniel Gagnon ^{a, c}, France Lambert ^a

^a Fiducie de recherche sur la forêt des Cantons-de-l'Est/Eastern Townships Forest Research Trust, 1 Rue Principale, Saint-Benoît-du-Lac, QC J0B 2M0, Canada

^b Département des sciences biologiques, Université du Québec à Montréal, C.P. 8888 succ. Centre-ville, Montréal, QC H3C 3P8, Canada

^c Department of Biology, University of Regina, 3737 Wascana Parkway, Regina, SK S4S 0A2, Canada

ARTICLE INFO

Article history:

Received 19 May 2014

Received in revised form

11 February 2015

Accepted 24 February 2015

Available online

Keywords:

Agroforestry

Aboveground biomass

Belowground biomass

Detrital biomass

C, N and P concentrations

Soil nutrient availability (supply rates)

ABSTRACT

In many temperate agricultural areas, riparian forests have been converted to cultivated land, and only narrow strips of herbaceous vegetation now buffer many farm streams. The afforestation of these riparian zones has the potential to increase carbon (C) storage in agricultural landscapes by creating a new biomass sink for atmospheric CO₂. Occurring at the same time, the storage of nitrogen (N) and phosphorus (P) in plant biomass, is an important water quality function that may greatly vary with types of riparian vegetation. The objectives of this study were (1) to compare C, N and P storage in aboveground, belowground and detrital biomass for three types of riparian vegetation cover (9-year-old hybrid poplar buffers, herbaceous buffers and natural woodlots) across four agricultural sites and (2) to determine potential vegetation cover effects on soil nutrient supply rate in the riparian zone. Site level comparisons suggest that 9-year-old poplar buffers have stored 9–31 times more biomass C, 4–10 times more biomass N, and 3–7 times more biomass P than adjacent non managed herbaceous buffers, with the largest differences observed on the more fertile sites. The conversion of these herbaceous buffers to poplar buffers could respectively increase C, N and P storage in biomass by 3.2–11.9 t/ha/yr, 32–124 kg/ha/yr and 3.2–15.6 kg/ha/yr, over 9 years. Soil NO₃ and P supply rates during the summer were respectively 57% and 66% lower in poplar buffers than in adjacent herbaceous buffers, potentially reflecting differences in nutrient storage and cycling between the two buffer types. Biomass C ranged 49–160 t/ha in woodlots, 33–110 t/ha in poplar buffers and 3–4 t/ha in herbaceous buffers. Similar biomass C stocks were found in the most productive poplar buffer and three of the four woodlots studied. Given their large and varied biomass C stocks, conservation of older riparian woodlots is equally important for C balance management in farmland. In addition, the establishment of poplar buffers, in replacement of non managed herbaceous buffers, could rapidly increase biomass C, N and P storage along farm streams, which would be beneficial for water quality protection and global change mitigation.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Worldwide, food systems contribute to 19–29% of anthropogenic greenhouse gas emissions, with agricultural production being responsible of 80–86% of emissions related to food systems

(Vermeulen et al., 2012). These emissions contribute to global change, which in turns threatens food security because of its potential adverse effects on agricultural yields (Lal et al., 2011; Vermeulen et al., 2012). Consequently, management strategies that reduce the carbon (C) footprint of agricultural production systems are essential for climate change mitigation and the sustainability of farming systems (Lal et al., 2011). Such strategies include afforestation and agroforestry to promote atmospheric CO₂ storage in plant biomass on degraded farmland, but also the production and use of renewable energy derived from woody biomass (Keith et al., 2009; Montagnini and Nair, 2004; Righelato and Spracklen, 2007). However, afforestation projects should not

* Corresponding author. Fiducie de recherche sur la forêt des Cantons-de-l'Est, 1 rue Principale, Saint-Benoît-du-Lac, QC J0B 2M0, Canada.

E-mail addresses: fortier.julien@courrier.uqam.ca (J. Fortier), btruax@frfce.qc.ca (B. Truax), daniel.gagnon@uregina.ca (D. Gagnon), france.lambert@frfce.qc.ca (F. Lambert).

cause excessive agricultural activity displacement, which could lead to deforestation elsewhere and negate C benefits, but also reduce food production and security (Campbell et al., 2008; Melillo et al., 2009).

In several temperate agricultural landscapes, riparian forests along farm streams have been cleared to increase cultivated areas and narrow strips of naturally regenerated herbaceous vegetation now line many of the once forested banks (Rheinhardt et al., 2012; Sweeney et al., 2004). These changes in vegetation cover have contributed to a marked decline of C stocks, but also a decline in other ecosystem services, including habitat for biodiversity and non-point source pollution abatement (Boutin et al., 2003; Jobin et al., 2004; Lowrance et al., 1997; Rheinhardt et al., 2012; Sweeney et al., 2004). Allowing forest to regrow in herbaceous-dominated riparian zones could be a promising strategy to increase C storage since C stocks along farm streams generally increase along the successional gradient. In the Coastal Plain of North Carolina (United States), mature riparian forests (>50 years-old) can store around 240 t/ha, which is 7–13 times higher than riparian zones dominated by perennial herbs, shrubby vegetation or row crops (Rheinhardt et al., 2012). In the Northeastern United States, white pine forests regenerated on abandoned farmland sites showed a linear increase in biomass C and N stocks in relation to time since abandonment (Hooker and Compton, 2003). These stock increases were mainly caused by the large gain in aboveground plant biomass that occurred along the chronosequence, with 9 t/ha observed 10 years after abandonment and 250–300 t/ha after a century (Hooker and Compton, 2003).

Promoting forest regrowth in agricultural riparian zones would contribute to water quality protection. Because they are interfaces between terrestrial and aquatic ecosystems, riparian zones control the movement and fate of different pollutants of farm streams, including nitrogen (N) and phosphorus (P), which are both responsible for eutrophication and water quality decline (Carpenter et al., 1998; McClain et al., 2003; Vidon et al., 2010). As reviewed by Di and Cameron (2002), nitrate leaching losses reaching more than 100 kg N/ha/yr have been found in both grazed pastures and arable cropping systems of the temperate zone. In Denmark, median losses of total N and total P in agricultural catchments reached 23.4 kg N/ha/yr and 0.29 kg P/ha/yr, while these losses were only 1.7 kg N/ha/yr and 0.07 kg P/ha/yr in undisturbed catchments, highlighting the contribution of agricultural activities to the non-point source pollution of streams (Kronvang et al., 1995). In this context, trees growing in riparian zones can uptake nutrients escaping from adjacent cultivated fields and contribute to long-term storage of those nutrients in biomass, thereby reducing the N and P loads that reach farm streams (Dosskey et al., 2010; Kelly et al., 2007).

However, in the absence of human intervention, forest regrowth in areas dominated by herbaceous vegetation may take several decades, sometimes a century, even if the surrounding vegetation is composed of woody species (Inouye et al., 1987; Maycock and Guzikowa, 1984). As an alternative to natural succession, tree plantations and agroforestry systems can be established, as buffers, in degraded riparian zones to increase C and nutrient storage, but also to improve local forest biodiversity (Brockerhoff et al., 2008; Chazdon, 2008; Fortier et al., 2012). For example, fast-growing hybrid poplars (*Populus* × spp.) have the potential to restore some forest attributes within a decade (Boothroyd-Roberts et al., 2013a), but also to promote rapid C stocks accumulation in plant biomass, compared to other farm land uses (Arevalo et al., 2009). There is growing evidence that over a few years after establishment, hybrid poplar buffers can become larger C and nutrient sinks in their biomass compared to non harvested herbaceous buffers of various compositions (Kelly et al.,

2007; Tufekcioglu et al., 2003). However, site fertility can have a significant effect on biomass growth, but also on C and nutrient storage of planted poplars (Fortier et al., 2010a,b; Truax et al., 2012).

While C storage in growing tree biomass is a sink for atmospheric CO₂, C storage in biomass can provide additional benefits in riparian zones. Organic C derived from decaying root biomass and leaf litter can fuel denitrification in waterlogged soils and streams, and contribute to water quality protection (Hill, 1996; Lowrance, 1992; Newcomer et al., 2012). In addition, litter may also have an important contribution to stream N and P budgets, a contribution that varies depending on types of riparian vegetation cover (Molinero and Pozo, 2006).

Presently, there is a lack of empirical data on the C and nutrient storage potential of different types of riparian vegetation cover in agricultural landscapes, with very little information regarding the distribution of C and nutrients in different biomass compartments, including decaying biomass (Rheinhardt et al., 2012; Tufekcioglu et al., 2003). There are also indications that for a particular riparian vegetation cover type, wide variations in C and nutrient stocks are observed between sites, at least for the different aboveground biomass compartments (Fortier et al., 2010b). In this context, evaluating the size and the variability of C and nutrient stocks in different biomass compartments, across different farmland settings, is important to understand the potential contribution of riparian agroforestry systems for C and nutrient management in agricultural landscapes. While tree buffers generally provide higher long-term nutrient storage capacity than herbaceous buffers, there is still little evidence that tree buffers are more effective than herbaceous buffers at reducing soil nutrient movement or availability across riparian zones (Dosskey et al., 2010; Mayer et al., 2007; Sabater et al., 2003). Additional studies are therefore needed to document the complex relationship between nutrient uptake, storage and release by biomass, and soil nutrient status in agricultural riparian buffers.

The present study aims at comparing C, N and P stocks in the different aboveground, belowground and detrital biomass compartments, of three types of riparian vegetation cover (9-year-old hybrid poplar buffers, herbaceous buffers and natural riparian woodlots) across four agricultural sites. Also, we evaluate the potential effects of these different vegetation cover types on soil nutrient availability (supply rate) in the riparian zone, with a specific emphasis on the comparison between poplar buffers and adjacent herbaceous buffers. We hypothesized that 9 year-old poplar buffers will store greater amounts of C, N and P in their biomass than adjacent herbaceous buffers, independent of the agricultural site studied. We also hypothesized that the greater nutrient storage in poplar buffers will result in a lower NO₃ and P availability in riparian soils during the growing season, when compared to adjacent herbaceous buffers.

2. Materials and methods

2.1. Study sites and experimental design

This study took place in the southern region of the province of Québec, Canada. At the four study sites (Bromptonville, Magog, Roxton Falls, St-Isidore-de-Clifton) three types of riparian vegetation cover were studied: (1) hybrid poplar riparian buffer, (2) herbaceous riparian buffer and (3) natural riparian woodlot. At each site, hybrid poplar riparian buffers were planted in spring 2003 at a density of 2222 stems per hectare on both sides of the streams for a total length of 90 m and a width of 4.5 m on each stream bank. These buffers are composed of 3 poplar rows, parallel to the stream, with a 1.5 m spacing between rows and a 3 m spacing between trees within a row. Bare-root hybrid poplar plants were 1 year-old

when they were planted. In the year of the study (2011), the buffers were in their 9th growing season. No site preparation was done prior to planting and tending operations consisted in a single localised herbicide treatment (1 m²/tree) in June 2003.

At each site, non managed (free-growing and non harvested) herbaceous buffers were located within 100 m upstream or downstream of the hybrid poplar buffers. These herbaceous buffers generally consisted of a mixture of native and exotic ruderal species that have naturally colonised the riparian zone (Fortier et al., 2011). The dominant species (in percent coverage) in these buffers were *Phleum pratense*, *Agropyron repens*, *Agrotis* spp., *Vicia cracca*, and *Solidago* spp. The non managed herbaceous buffers were protected by a fence for at least two years at the three pasture sites to prevent livestock grazing.

At each site, a natural riparian woodlot, located as close as possible from both buffer types, was selected. These woodlots were located 1 km or less upstream of the poplar or herbaceous buffers. The 4 riparian woodlots were very different among the sites: (1) a 200-year-old eastern hemlock (*Tsuga canadensis*) stand at Bromptonville; (2) a 73-year-old eastern white cedar (*Thuja occidentalis*) stand (where livestock had free access) at Magog; (3) a 27-year-old grey birch (*Betula populifolia*) stand at Roxton Falls, and (4) a 54-year-old sugar maple (*Acer saccharum*) stand at St-Isidore-de-Clifton. The age of these stands was estimated by coring the dominant trees. Basal areas of these riparian woodlots were 61 m²/ha for the hemlock woodlot, 60 m²/ha for the white cedar woodlot, 24 m²/ha for the grey birch woodlot and 29 m²/ha for the sugar maple woodlot.

Based on personal communications with landowners, we have gathered the following information concerning land use history at each site. At all sites, both types of riparian buffers are located in areas that were deforested at least 50 years ago. The riparian woodlots of Magog, Roxton Falls and St-Isidore are secondary forests regenerated in abandoned pastures, and the woodlot of Brompton has never been cultivated or completely deforested (primary forest). At Bromptonville, the pasture adjacent to both types of riparian buffers supports a cattle density of 0.6 cow/ha and is fertilised on an annual basis with cattle manure. At Magog, the pasture adjacent to both types of riparian buffers supports a cattle density of 0.2 cow/ha and has never been fertilised. At Roxton Falls, the hayfield adjacent to the poplar buffer was fertilised each year with cow manure, but this stopped in 2009, when poplars were in their 7th growing season. The herbaceous buffer at the Roxton Falls site is adjacent to a cultivated field that is fertilised each year with cow manure and pig slurry. This field is subjected to crop rotation (hay and soy), with soy being the crop grown in the year of the study (2011). At St-Isidore-de-Clifton, the pasture adjacent to both types of riparian buffers supports a cattle density of 0.5 cow/ha and is fertilised each year with cow manure, and every five years, with 18 kg/ha of inorganic N fertiliser and 800 kg/ha of lime. The last time the N fertiliser was applied was in July 2011. Site characteristics for the different types of riparian vegetation cover are summarized in Table 1. Additional information on soil properties distribution down the soil profiles can be consulted in a companion study (Fortier et al., 2013b).

In the hybrid poplar buffer vegetation cover, a randomized block design was used at each of the 4 sites, with 4 blocks (replicates) and 3 hybrid poplar clones: (1) *Populus deltoides* × *nigra* (DxN-3570; also named *Populus* × *canadensis*); (2) *P. canadensis* × *maximowiczii* (DNxM-915508); and (3) *Populus maximowiczii* × *balsamifera* (MxB-915311). A total of 48 hybrid poplar riparian buffer experimental plots were sampled in this study. These plots are 4.5 m wide and 9 m long (40.5 m²). Each plot contains 9 trees from a single clone (3 rows; 3 trees per row). At each site, four herbaceous buffer plots were sampled (n = 16, 4 sites × 4 plots/site). The size of the

Table 1

Site characteristics of three types of vegetation covers at four agricultural sites in southern Québec, Canada.

Vegetation cover	Site	Description (dominant tree age)	Elevation
Woodlot – Hemlock	Brompton	Primary forest (200 yrs)	200
Woodlot – W. Cedar	Magog	Secondary forest – livestock access (72 yrs)	220
Woodlot – G. Birch	Roxton	Secondary forest (27 yrs)	145
Woodlot – S. Maple	St-Isidore	Secondary forest (54 yrs)	420
Hybrid poplar buffer	Brompton	Buffer in fertilised pasture (9 yrs)	140
Hybrid poplar buffer	Magog	Buffer in pasture (9 yrs)	210
Hybrid poplar buffer	Roxton	Buffer in hayfield (9 yrs)	145
Hybrid poplar buffer	St-Isidore	Buffer in fertilised pasture (9 yrs)	360
Herbaceous buffer	Brompton	Buffer in fertilised pasture	140
Herbaceous buffer	Magog	Buffer in pasture	200
Herbaceous buffer	Roxton	Buffer in fertilised row crop/hayfield	140
Herbaceous buffer	St-Isidore	Buffer in fertilised pasture	380

herbaceous buffer plots was 4.5 m (poplar buffer width) × 9 m (40.5 m²). At each site, there were 4 riparian woodlot plots (n = 16, 4 sites × 4 plots/site). The size of these woodlot plots was 4.5 m × 9 m (40.5 m²).

In this study, the entire experimental design contains 80 experimental plots covering three types of riparian vegetation cover: (1) 48 hybrid poplar riparian buffer plots; (2) 16 non managed herbaceous riparian buffer plots; (3) 16 riparian woodlot plots.

2.2. Nitrogen and phosphorus supply rate in surface soil

Nitrate and P supply rate in the entire experimental design were determined using Plant Root Simulator (PRS™-Probes) technology from Western Ag Innovations Inc. Saskatoon, Canada. The PRS-probes consist of ion exchange membranes encapsulated in thin plastic probes, which were inserted vertically in the surface soil (0–10 cm) with little disturbance of soil structure. The membrane surface exhibits surface and sorption characteristics similar to those of a plant root. Nutrient supply rates measured with this method are generally significantly correlated with conventional soil extraction methods over a wide range of soil types (Qian et al., 1992). PRS-probes have also been recently useful in detecting mineral-N and P hot spots in forest soils (Johnson et al., 2010).

In August 2011, four pairs of probes (an anion and a cation probe in each pair) were buried in the A horizon of each plot (n = 80) for a 20-day period. After probes were removed from the soil, they were washed in the field with deionised water, and returned to Western Ag Labs for NO₃ and P analysis. Composite samples were made in each plot by combining the four pairs of probes. Probe supply rates are reported as µg of nutrient 10 cm²/20 d.

2.3. Aboveground biomass sampling

In the hybrid poplar buffers, stem and branch biomass were calculated for each individual tree using diameter at breast height (DBH) measurements (made in Fall 2011) and allometric relationships developed at the end of the 9th growing season in the same

experimental design (Fortier et al., 2013a). In woodlots, stem and branch biomass, but also leaf biomass of coniferous species, were calculated using DBH measurements (made in Fall 2011) of each tree, and species specific allometric relationships found in the literature (Ter-Mikaelian and Korzukhin, 1997). It should be mentioned that the studied riparian woodlot plots were located at the forest's edge, while the selected allometric relationships had been developed for trees growing in interior forests. Consequently, it is possible that we have underestimated biomass and C, N and P stocks in branches and leaves of the studied woodlot plots because trees growing at the forest edge tend to have greater biomass allocation to branches and leaves than trees growing in the forest interior (Mourelle et al., 2001; Zhou et al., 2011). Total biomass of the different aboveground tree compartments was calculated at the plot level by summing biomass values calculated for the different compartments of each tree. Stem (including bark) and branch subsamples were collected from each hybrid poplar buffer and woodlot plots to determine C, N and P concentrations. These subsamples were only taken from the dominant tree species in woodlot plots. The same procedure was used for leaves in the woodlots dominated by a coniferous species. In each plot, herbaceous vegetation biomass was sampled by clipping vegetation in three 50 × 50 cm microplots at the end of July 2011. Plot-level subsamples were collected to determine dry weight and C, N and P concentrations.

2.4. Belowground biomass sampling

In this study the term belowground biomass represents the sum of fine and coarse root biomass. In each plot, belowground biomass was sampled to a 60 cm soil depth from mid-June to mid-July 2011. The coring technique was used for fine root biomass sampling (diameter < 2 mm). Fine root biomass includes both live and dead root mass. In each plot (n = 80), coarse root biomass (diameter > 2 mm) samples were obtained by excavating pits (50 × 50 cm by 60 cm deep) and harvesting all coarse roots in the pits. Root samples were washed with water and air dried. Coarse root samples collected in each plot were used to determine dry weight, and C, N and P concentrations. At each site, fine root samples collected in each plot were combined at the vegetation cover level prior to chemical analyses.

2.5. Detrital biomass sampling

In this study the term detrital biomass includes four different compartments: (1) fresh leaf litter collected after leaf fall, (2) O horizon of the soil sampled in late summer prior to leaf fall, (3) coarse woody debris and (4) fine woody debris. Hybrid poplar leaf litter biomass was determined for individual trees using DBH measurements made in Fall 2011 and allometric relationships developed to calculate leaf biomass of individual trees in hybrid poplar riparian buffers (Fortier et al., 2010a). This procedure was preferred to litterfall trap biomass measurements given that an important proportion of poplar leaf litter is blown away from the poplar buffer by wind, and falls directly into stream water or on adjacent pastures or cultivated fields. The same procedure was used to calculate leaf litter biomass in the grey birch and sugar maple woodlot stands using published allometric relationships for leaf biomass (Ter-Mikaelian and Korzukhin, 1997). However, one litterfall trap (36 × 50 cm) was installed in late August 2011, in each plot containing deciduous trees to collect litterfall biomass for chemical analysis. Only leaf material was taken from the litterfall samples to determine carbon and nutrient concentrations and contents. The O horizon was sampled only in the oldest riparian woodlots (hemlock, white cedar and sugar maple) because the grey

birch stand and the poplar buffers had no O horizon prior to leaf fall. In mid-August 2011, in each plot of the older woodlot stands, the O horizon biomass was sampled by harvesting the organic soil layer found in three 50 × 50 cm microplots. In each sampled plot, a subsample was collected to determine dry weight, and C, N and P concentrations.

In each riparian woodlot plot (n = 16), small woody debris (large end diameter 1–10 cm) (Harmon et al., 2008) were collected on the whole plot surface (4.5 m × 9 m) and weighed in the field. Small woody debris subsamples were taken back to the lab to determine dry weight, C, N and P concentrations. Fine woody debris biomass was marginal in the poplar buffers and was not sampled. Coarse woody debris measurements include all dead woody material both standing and down that had a small end diameter larger than 10 cm (Harmon et al., 2008). In the older riparian woodlot stands (hemlock, white cedar and sugar maple), the volume of each piece of coarse woody debris was measured. The species was determined for each piece of woody debris. A decomposition class from 1 to 5 was attributed to each piece of coarse woody debris based on the penetration depth of a knife (Rouvinen et al., 2002). The biomass of each piece of coarse woody debris was calculated by multiplying volume by woody debris density. Coarse woody debris densities for different tree species and decomposition classes were obtained from the literature (Harmon et al., 2008). In each plot, coarse woody debris subsamples from the largest woody debris were collected to determine C, N and P concentrations. Total coarse woody debris biomass was calculated at the plot level by summing the biomass of individual coarse woody debris.

2.6. Carbon, nitrogen and phosphorus concentration and stocks in biomass

All biomass subsamples were ground in a mill (Pulverisette 15, Fritsch) to a particle size of <0.5 mm to insure adequate sample homogeneity. Phosphorus concentration was determined by the calcination method (AOAC, 1999) at the Agridirect laboratory, Longueuil (Qc, Canada). For biomass C and N concentration determinations, ground, dried aliquots of plant samples (approximately 100 mg) were encapsulated in tin prior to analysis. Total C and N were determined by high-temperature combustion (960 °C) of the samples, followed by thermo-conductometric detection, on a Vario Macro analyzer (Elementar Analysensysteme, Hanau, Germany). Measurements were standardized against glutamic acid, together with checks on N recovery using NIST (National Institute of Standards and Technology, Gaithersburg, MD) reference materials (Citrus 1572, Apple 1515). These analyses were done by the CEF lab (Dr. R. Bradley and Dr. W. Parsons) at the University of Sherbrooke. In each plot, nutrient and C stocks in the different biomass compartments were obtained by multiplying C, N and P concentrations determined in subsamples by the total biomass of the compartment.

2.7. Statistical analysis and assumptions

In this study, we hypothesized that poplar buffers will store greater amounts of C, N and P in their biomass than adjacent herbaceous buffers, independent of the agricultural site studied. In that perspective, it was statistically relevant to look for potential site level differences in storage potential of different vegetation cover types. We were also interested in evaluating the size and the variability of C and nutrient stocks in different biomass compartments, of the different riparian vegetation cover types, across different farmland settings. Consequently, the effect of hybrid poplar clone (genotype) selection on C and nutrient storage was not the focus of this study, as we have already reported significant

Clone effects on aboveground biomass differences after 9 years, and on aboveground C and nutrient storage after 6 years (Fortier et al., 2010b, 2013a). To remove variability associated to the hybrid poplar clones sampled, we used the averaged measured variables of the 3 clones within a block, in order to produce data at the block level. Consequently, for statistical analysis, the number of plots in the hybrid poplar buffer vegetation cover was reduced from 48 to 16 plots, which is equal to the number of plots sampled in the two other types of riparian vegetation cover (herbaceous buffer and riparian woodlot). Thereafter, a series of ANOVAs was used to evaluate the riparian Vegetation cover and Site effects and Vegetation cover × Site interaction on biomass, C and nutrient concentration and stock variables. The model for each ANOVA included 3 types of vegetation cover (hybrid poplar buffer, herbaceous buffer, riparian woodlot) and 4 sites (Bromptonville, Magog, Roxton Falls, St-Isidore-de-Clifton) and 4 replicates of each type of riparian vegetation cover at each site (3 types of vegetation cover × 4 sites × 4 replicates = 48 plots). However, for the poplar buffer and herbaceous buffer vegetation cover types, certain biomass compartments had no biomass value and no C or nutrient stocks. Consequently, they were removed from the analysis for these biomass compartments. For the comparison of riparian soil NO₃ and P supply rates in the two types of agricultural riparian buffers (herbaceous and hybrid poplar), we removed the Roxton site from the analysis. This is because at the Roxton site the poplar buffer and the herbaceous buffer are not bordered by the same agricultural land use; the poplar buffer borders an unfertilised hayfield, while the herbaceous buffer borders a fertilised row crop field (soy) (Table 1). Consequently, the two buffer types are not receiving similar nutrient input, making comparisons for soil nutrient supply rates inappropriate at this particular site. For the presentation of results in figures, abbreviations of the names of plantation sites were used (Bromptonville = Bro, Magog = Mag, Roxton Falls = Rox, St-Isidore-de-Clifton = Sti).

In this study, we calculated the gain in C and nutrient storage that would be associated with the conversion of non managed (non harvested) herbaceous buffers into hybrid poplar buffers. This calculation is based on the assumption that the studied herbaceous buffers had reached a steady-state or equilibrium point in terms of biomass production. Consequently, from year-to-year, biomass increments of non harvested herbaceous buffers are assumed to be nil, and nutrient input equals output (Vitousek and Reiners, 1975). This assumption is based on the fact that these herbaceous communities were established more than 50 years ago and were protected from grazing for two years, at Bromptonville and Magog, and for 9 years at St-Isidore-de-Clifton.

3. Results

3.1. Carbon, nitrogen and phosphorus stocks in aboveground biomass

Aboveground C, N and P stocks varied greatly between riparian vegetation cover types and sites (Table 2). Aboveground C stocks ranged from 42 to 115 t/ha in natural woodlots, 25–91 t/ha in hybrid poplar buffers, and 2–3 t/ha in herbaceous buffers. Aboveground N stocks ranged from 391 to 978 kg/ha in natural woodlots, 277–872 kg/ha in hybrid poplar buffers, and 82–96 kg/ha in herbaceous buffers. Aboveground P stocks ranged from 42 to 124 kg/ha in natural woodlots, 31–105 kg/ha in hybrid poplar buffers, and 11–22 kg/ha in herbaceous buffers (Table 2). The majority of aboveground C, N and P stocks of natural woodlots and poplar buffers were located in stem biomass. Higher N and P concentrations (p < 0.001) were found in hybrid poplar branches when compared to woodlot species (Appendix 1).

Table 2 Carbon, nitrogen and phosphorus stocks in aboveground biomass compartments for the three types of vegetation cover at the four sites.

Vegetation cover	Site	Stems			Branches			Leaves			Herbaceous			Aboveground total								
		Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)					
Woodlot – Hemlock	Brompton	187	86.3	473	74.7	37.1	16.7	130	11.1	25.6	12.0	373	37.7	0.11	0.05	1.6	0.2	250	115	978	124	
Woodlot – W. Cedar	Magog	155	73.3	444	62.0	37.6	17.4	148	14.1	21.1	9.9	263	20.4	0.03	0.01	1.0	0.1	214	101	856	97	
Woodlot – G. Birch	Roxton	83	36.8	288	33.1	9.1	4.1	49	2.7	–	–	–	–	2.64	1.09	54.3	6.5	95	42	391	42	
Woodlot – S. Maple	St-Isidore	157	69.0	482	53.8	24.2	10.1	97	7.3	–	–	–	–	0.48	0.21	10.7	0.7	182	79	591	62	
Hybrid poplar buffer	Brompton	142	66.7	480	56.6	50.7	23.8	364	44.2	–	–	–	–	1.57	0.61	28.3	4.6	194	91	872	105	
Hybrid poplar buffer	Magog	38	17.7	137	14.2	13.5	6.4	91	11.1	–	–	–	–	3.32	1.25	48.8	5.6	55	25	277	31	
Hybrid poplar buffer	Roxton	76	35.3	256	29.3	26.7	12.5	166	18.5	–	–	–	–	2.29	0.91	37.7	4.0	105	49	460	52	
Hybrid poplar buffer	St-Isidore	88	41.2	336	32.2	31.3	14.6	212	21.2	–	–	–	–	1.08	0.44	20.7	2.5	121	56	569	56	
Herbaceous buffer	Brompton	–	–	–	–	–	–	–	–	–	–	–	–	6.06	2.23	92.9	19.8	6	2	93	20	
Herbaceous buffer	Magog	–	–	–	–	–	–	–	–	–	–	–	–	5.74	2.22	81.7	11.2	6	2	82	11	
Herbaceous buffer	Roxton	–	–	–	–	–	–	–	–	–	–	–	–	4.71	1.92	90.2	12.6	5	2	90	13	
Herbaceous buffer	St-Isidore	–	–	–	–	–	–	–	–	–	–	–	–	6.93	2.88	96.3	22.4	7	3	96	22	
Vegetation × Site	SE	29	13.7	83	11.5	5.9	2.7	25	3.3	–	–	–	–	0.26	0.11	6.5	3.1	30.9	14.4	115	14	
	p <	NS	NS	NS	NS	0.01	0	0.001	0.001	–	–	–	–	0.001	0.001	0	NS	NS	NS	0.05	0.05	0.05
Vegetation	p <	0.01	0.05	NS	0.01	NS	NS	0.001	0.001	–	–	–	–	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Site	p <	0.05	0.01	NS	0.05	0.01	0	0.001	0.001	NS	NS	NS	NS	0.05	0.01	0.01	NS	0.05	0.05	0.05	0.01	0.01

3.2. Carbon, nitrogen and phosphorus stocks in belowground biomass

Belowground C, N and P stocks also varied greatly between riparian vegetation cover types and sites (Table 3). Belowground C stocks ranged from 5.2 to 36.8 t/ha in natural woodlots, 4.8–13 t/ha in hybrid poplar buffers, and 1.3–1.6 t/ha in herbaceous buffers. Belowground N stocks ranged from 94 to 398 kg/ha in natural woodlots, 64–177 kg/ha in hybrid poplar buffers, and 27–62 kg/ha in herbaceous buffers. Belowground P stocks ranged from 9.7 to 33.6 kg/ha in natural woodlots, 10.2–41.1 kg/ha in hybrid poplar buffers, and 4.8–8.8 kg/ha in herbaceous buffers. High P concentrations were found in hybrid poplar coarse roots (0.08–0.16%) compared to what was measured in the hemlock, white cedar and sugar maple woodlots (0.04%) (Appendix 2).

3.3. Carbon, nitrogen and phosphorus stocks in detrital biomass

Detrital C, N and P stocks (excluding mineral soil) also varied greatly between riparian vegetation cover types and sites (Table 4). We assumed that herbaceous buffers had no detrital C and nutrient stocks because detrital biomass of herbaceous buffers would mainly originate from the death of aboveground herbaceous biomass during the fall. Detrital C stocks ranged from 2.3 to 12.3 t/ha in natural woodlots, and from 2.3 to 6.1 t/ha in hybrid poplar buffers. Detrital N stocks ranged from 43 to 194 kg/ha in natural woodlots, and from 52 to 200 kg/ha in hybrid poplar buffers. Detrital P stocks ranged from 3.1 to 16.7 kg/ha in natural woodlots, and from 4.2 to 19.8 kg/ha in hybrid poplar buffers. While detrital C, N and P stocks were mainly located in the soil O horizon and coarse woody debris in older woodlots, the detrital stocks were mostly located in fresh leaf litter in the poplar buffers and in the grey birch stand (Table 4).

3.4. Total carbon, nitrogen and phosphorus stocks in biomass

Total C, N and P stocks in biomass (aboveground + belowground + detrital) also varied greatly between riparian vegetation cover types and sites (Fig. 1). Total C stocks in biomass ranged from 49 to 160 t/ha in natural woodlots, 33–110 t/ha in hybrid poplar buffers, and 3–4 t/ha in herbaceous buffers. Total N stocks in biomass ranged from 528 to 1566 kg/ha in natural woodlots, 393–1248 kg/ha in hybrid poplar buffers, and

109–152 kg/ha in herbaceous buffers. Total P stocks in biomass ranged from 55 to 172 kg/ha in natural woodlots, 45–166 kg/ha in hybrid poplar buffers, and 16–31 kg/ha in herbaceous buffers.

For the three types of riparian vegetation cover, the majority of C, N and P stocks in biomass were located in the aboveground biomass (Fig. 1). Carbon, N and P stocks in aboveground biomass respectively accounted for 72–85%, 59–74% and 70–77% of total biomass stocks in natural woodlots, 78–83%, 70–73% and 63–68% of total biomass stocks in hybrid poplar buffers, and 55–64%, 59–75% and 59–78% of total biomass stocks in herbaceous buffers.

3.5. Soil nitrate and phosphorus supply rates

A significant Vegetation cover × Site interaction was observed for NO₃ supply rates measured in riparian soils ($p < 0.001$). The greatest NO₃ supply rate measured over a 20-day period (August 2011) was not observed in a riparian buffer, but in the white cedar riparian woodlot at Magog, where livestock (cows) have free access (Fig. 2, Table 1). At this site, the NO₃ supply rate observed in the cedar stand (280 µg/10 cm²/20 d) contrasts sharply with observed supply rates in the herbaceous buffer (19 µg/10 cm²/20 d) and the poplar buffer (10 µg/10 cm²/20 d). A significant Vegetation cover × Site interaction was also observed for P supply rate ($p < 0.05$), with P supply rate being especially high in the herbaceous buffer at Brompton, compared to the adjacent poplar buffer. In general, soil P supply rates in poplar buffers were similar to those of natural woodlots, but were similar to or lower than soil P supply rates in herbaceous buffers (Fig. 2). After removing the riparian woodlot plots from the ANOVA, we also observed significant Vegetation cover effects on soil NO₃ ($p < 0.001$) and P ($p < 0.01$) supply rates in riparian buffer zones (Fig. 2). Across three sites (Brompton, Magog and St-Isidore), our results suggest that NO₃ and P supply rates in riparian soil were respectively 57% and 66% lower in poplar buffers compared to those in herbaceous buffers.

4. Discussion

4.1. Nitrogen and phosphorus storage in biomass and its effect on soil nutrient supply rates

Site level comparisons between agricultural buffer types suggest that 9-year-old poplar buffers have stored 4–10 times more biomass N and 3–7 times more biomass P than adjacent

Table 3
Carbon, nitrogen, phosphorus stocks in belowground biomass compartments for the three types of riparian vegetation cover at the four sites.

Vegetation cover	Site	Coarse roots				Fine roots				Belowground total			
		Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)
Woodlot-Hemlock	Brompton	73.7	33.3	324	25.9	8.48	3.40	73.9	7.68	82.2	36.8	398	33.6
Woodlot – W. Cedar	Magog	29.8	13.9	185	10.7	4.77	2.17	61.4	4.45	34.6	16.1	246	15.2
Woodlot – G. Birch	Roxton	8.8	4.0	66	7.3	2.68	1.20	27.5	2.41	11.4	5.2	94	9.7
Woodlot – S. Maple	St-Isidore	26.7	12.0	146	9.1	8.64	3.77	72.4	4.73	35.3	15.8	218	13.9
Hybrid poplar buffer	Brompton	27.3	12.1	154	38.3	2.28	0.98	22.8	2.81	29.6	13.0	177	41.1
Hybrid poplar buffer	Magog	9.2	4.0	49	8.7	1.86	0.81	14.2	1.49	11.0	4.8	64	10.2
Hybrid poplar buffer	Roxton	20.8	9.2	76	15.2	2.62	1.06	20.0	2.54	23.4	10.2	96	17.7
Hybrid poplar buffer	St-Isidore	12.9	5.7	65	13.1	1.91	0.82	17.3	1.88	14.8	6.5	82	14.9
Herbaceous buffer	Brompton	0.6	0.3	5	1.0	2.60	1.08	30.5	4.68	3.2	1.3	35	5.7
Herbaceous buffer	Magog	0.6	0.3	4	0.9	2.80	1.09	23.5	3.90	3.4	1.3	27	4.8
Herbaceous buffer	Roxton	1.1	0.4	12	1.6	3.29	1.15	50.3	7.19	4.4	1.6	62	8.8
Herbaceous buffer	St-Isidore	1.3	0.5	15	2.9	2.79	1.10	36.1	5.38	4.0	1.6	51	8.3
Vegetation × Site	SE	2.5	1.1	13	2.7	0.45	0.18	4.9	0.84	2.6	1.2	14	3.0
	p<	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.01	0.001	0.001	0.001	0.001
Vegetation	p<	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Site	p<	0.001	0.001	0.001	0.001	0.001	0.001	0.05	NS	0.001	0.001	0.001	0.001

Table 4
Carbon, nitrogen and phosphorus stocks in detrital biomass compartments (excluding mineral soil) for the two types of riparian vegetation cover at the four sites.

Vegetation cover	Site	Fresh litter			O Horizon			Coarse woody debris			Fine woody debris			Detrital total								
		Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)	Biomass (t/ha)	C (t/ha)	N (kg/ha)	P (kg/ha)					
Woodlot – Hemlock	Brompton	–	–	–	–	11.3	4.19	137	11.6	3.9	1.80	36.5	1.99	3.49	1.69	17.2	1.05	18.7	7.7	190	14.6	
Woodlot – W. Cedar	Magog	–	–	–	–	11.9	3.87	148	13.1	9.9	4.66	28.7	2.98	2.34	1.14	8.9	0.70	24.2	9.7	185	16.7	
Woodlot – G. Birch	Roxton	2.4	1.17	32	2.3	–	–	–	–	–	–	–	–	2.35	1.11	10.7	0.81	4.8	2.3	43	3.1	
Woodlot – S. Maple	St-Isidore	4.5	1.99	35	1.8	4.9	2.05	92	5.0	17.1	7.71	62.5	5.16	1.21	0.57	5.2	0.36	27.7	12.3	194	12.4	
Hybrid poplar buffer	Brompton	14.4	6.10	200	19.8	–	–	–	–	–	–	–	–	–	–	–	–	14.4	6.1	200	19.8	
Hybrid poplar buffer	Magog	5.5	2.34	52	4.2	–	–	–	–	–	–	–	–	–	–	–	–	5.5	2.3	52	4.2	
Hybrid poplar buffer	Roxton	9.3	3.81	91	7.8	–	–	–	–	–	–	–	–	–	–	–	–	9.3	3.8	91	7.8	
Hybrid poplar buffer	St-Isidore	11.0	4.64	125	12.0	–	–	–	–	–	–	–	–	–	–	–	–	11.0	4.6	125	12.0	
Vegetation × Site	SE	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4.7	2.1	29	2.3
Vegetation	p <	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	NS	NS	0.05	0.01
Site	p <	–	–	–	–	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.05	0.05	NS	NS	NS	NS	NS
Site	p <	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	NS	NS	0.01	0.001

herbaceous buffers (Fig. 1). The larger differences in nutrient storage between the two buffer types were observed on the more fertile sites (Brompton, St-Isidore and Roxton), in terms of soil NO₃ and P supply rates (Fig. 2). Poplar biomass growth is greatly increased when soil NO₃ and P availability increase in riparian soils (Fortier et al., 2010a, 2013a), while the biomass growth of herbaceous buffers seems influenced to a much lesser extent by site fertility (Tables 2 and 3). On a mean annual basis, the conversion of non harvested herbaceous buffers into hybrid poplar buffers could respectively increase N and P storage in biomass by 32–124 kg/ha/yr and by 3.2–15.6 kg/ha/yr (Table 5). These increases in storage potential are likely related to the different biomass turnover times of those two different vegetation cover types, with poplar biomass having a longer mean residence time (several years), while aboveground biomass of herbaceous communities will grow and decay on an annual basis. At many sites, N and P stored in biomass of poplar buffers was also comparable to values found in riparian woodlots (Fig. 1). This suggests that within a decade hybrid poplars can accumulate nutrients in biomass along farm streams to levels that are found in much older natural riparian woodlots.

The high N and P storage in poplar buffers may also explain the much lower NO₃ and P supply rates measured during the summer in riparian soils (0–10 cm) of poplar buffers, compared to adjacent herbaceous buffers (Fig. 2). Across the three study sites (Roxton site excluded), riparian soil NO₃ and P supply rates were respectively 57% and 66% lower in poplar buffers than in adjacent herbaceous buffers, with the Vegetation cover effect being significant at p < 0.001 for soil NO₃ and at p < 0.01 for soil P supply rates (Fig. 2). It is likely that poplar buffers contribute more to reducing soil NO₃ leaching from agricultural fields to stream waters than non harvested herbaceous buffers, because NO₃ leaching is generally higher when soil NO₃ content or bioavailability is higher (Di and Cameron, 2002). Lower concentrations of bioavailable P in buffer soils have also been associated to potentially lower P loss in sub-surface flow (Aye et al., 2006).

It is also possible that lower soil NO₃ and P supply rates in poplar buffers were mediated by hydrological factors. In the study region (southern Québec), soil water content measured in August in eight 10 year-old hybrid poplar plantations was on average 25% lower than in adjacent abandoned fields, most of them dominated by a herbaceous cover (Boothroyd-Roberts et al., 2013a). Tree buffers are expected to have higher evapotranspiration rates than herbaceous buffers because of their higher leaf surface area, biomass and exposure to wind (Dosskey et al., 2010). In other words, soils may dry out more quickly under poplars in the summer, which may reduce NO₃ and P mobility in soil, compared to soils in adjacent herbaceous buffers.

Particular functional traits, in terms of rooting habit and nutrient storage strategies, of fast-growing hybrid poplars may have contributed to the high biomass N and P storage and the lower soil NO₃ and P supply rates in poplar buffers. Poplar roots can extend laterally several metres away from the riparian zones, and uptake nutrients in soil underneath adjacent pastures or cultivated fields (Fortier et al., 2013b), thereby reducing the N and P load before it reaches the buffer zone. Lateral rooting extending 32 m away from a poplar tree base has been reported in the Prairies (Buell and Buell, 1959). Poplars are also deeply rooted in riparian soils, while the root system of the non managed herbaceous buffers is almost entirely restricted to the 0–20 cm soil depth (Fortier et al., 2013b). Thus, compared to herbaceous buffers, uptake of resources occurs in a much larger soil volume in poplar buffers, both laterally and vertically. In addition, parental species of poplar hybrids used in this study are all natural floodplain species (Dickmann and Kuzovkina, 2008). These floodplain poplars have the ability to respond to high periodic N inputs, following flooding, by

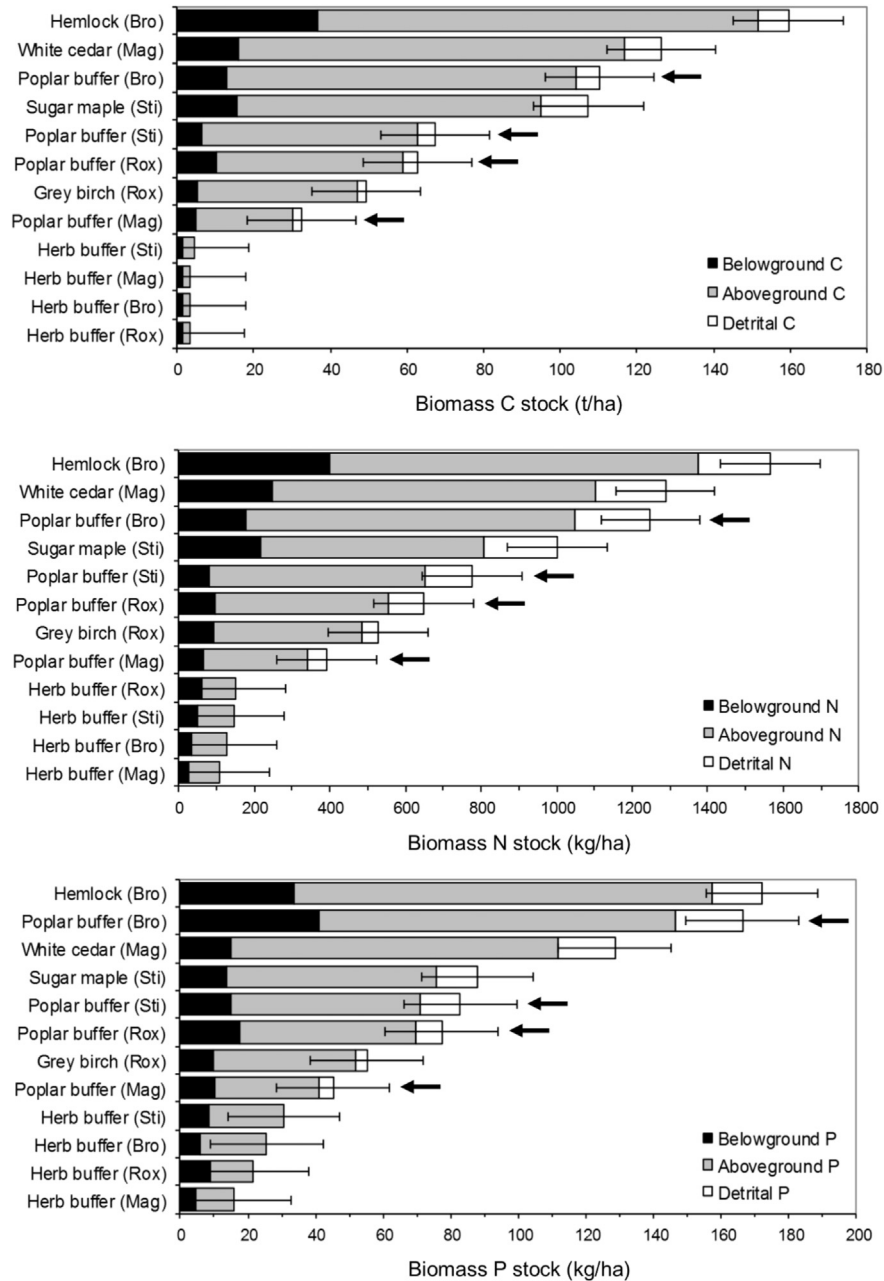


Fig. 1. Total C, N and P stocks in biomass and their distribution between belowground, aboveground and detrital biomass (excluding mineral soil) in three types of vegetation cover (herbaceous buffer, hybrid poplar buffer and natural riparian woodlot) across four sites. Vegetation cover × Site interactions for total C, N and P stocks are significant at $p < 0.001$. Horizontal bars represent SE. Black arrows highlight the hybrid poplar buffers.

temporarily increasing their N storage in the form of protein, for subsequent use (Bradshaw et al., 2000). Consequently, during the growing season, poplars have the physiological capacity to store high nutrient loads migrating from adjacent pastures or cultivated fields during episodes of high nutrient transport, which typically occur during or following heavy precipitation events. Furthermore, both poplar growth and aboveground tissue nutrient concentrations can be enhanced by site fertility, resulting in a synergetic effect on total nutrient storage at sites where the nutrient load is higher (Fortier et al., 2010b). This positive concentration effect (Jarrell and Beverly, 1981) was mainly observed for poplar belowground tissues and leaf litter in this study, with highest N and P concentrations in those compartments observed at sites where soil NO₃ and P supply rates were higher (Brompton and St-Isidore)

(Fig. 2, Appendices 2 and 3). Hybrid poplar N and P concentrations in branches and coarse roots also tended to be much higher than what was observed for most woodlots species, while tissue C concentrations were comparable between the two cover types (Appendices 1 and 2). As a result, although the poplar buffer at Brompton had similar biomass C compared to the sugar maple and white cedar woodlots, this poplar buffer had higher P stocks (Fig. 1).

Even though poplars stored large amounts of N and P in their biomass, an important fraction of these nutrients is only temporarily immobilised in leaf litter (Table 4). Nitrogen and P stocks in poplar leaf litter respectively ranged from 52 to 200 kg/ha and from 4.2 to 19.8 kg/ha, accounting for 13–16% of total N storage in biomass and 9–14% of total P storage in biomass. These nutrients will gradually be released back or cycled into the soil and stream, as

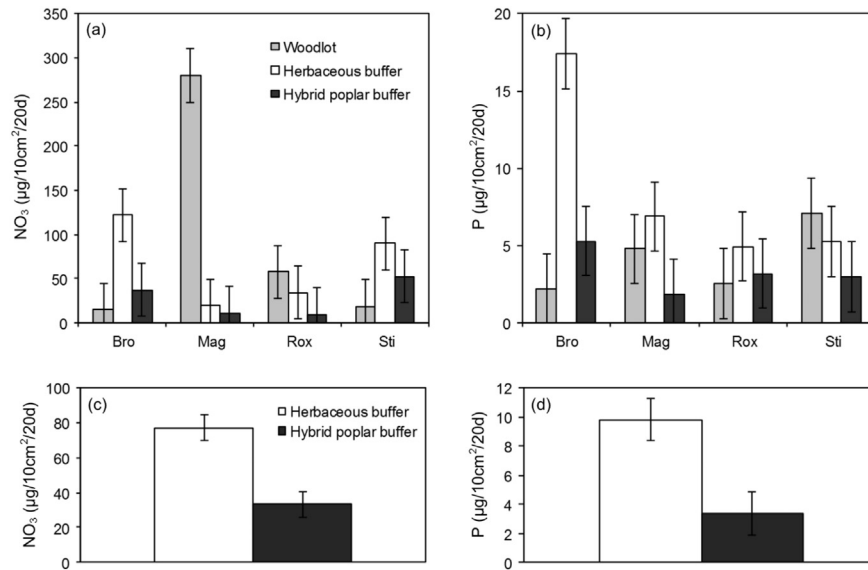


Fig. 2. Nitrate and P supply rates in surface soil (0–10 cm) under different types of riparian vegetation cover, measured during 20 days in August 2011. Vegetation cover \times Site interactions on (a) NO₃ ($p < 0.001$) and (b) P ($p < 0.05$) supply rates. Vegetation cover effects (three site mean) on (c) NO₃ ($p < 0.001$) and (d) P ($p < 0.01$) supply rates. The Roxton site has been removed from the analysis (panels c and d) because the poplar buffer and the herbaceous buffer were not bordered by the same agricultural land use at this site. Vertical bars represent SE in all panels.

Table 5

Total biomass (aboveground, belowground and detrital) carbon, nitrogen and phosphorus storage increases after 9 years following the replacement of non harvested herbaceous riparian buffers by hybrid poplar buffers. Carbon and nutrient stocks in herbaceous buffers are assumed to be constant through time because community biomass has reached its equilibrium point.

Site	Storage increase after 9 years			Annual storage increase		
	Biomass C (t/ha)	Biomass N (kg/ha)	Biomass P (kg/ha)	Biomass C (t/ha/yr)	Biomass N (kg/ha/yr)	Biomass P (kg/ha/yr)
Brompton	107	1120	141	11.9	124	15.6
Magog	29	284	29	3.2	32	3.2
Roxton	59	495	56	6.6	55	6.2
St-Isidore	63	628	52	7.0	70	5.8

litter is decomposed. Being essentially composed of fresh litter of high quality, the biomass detrital pool of poplar buffers is expected to have a much greater turnover rate than the detrital biomass pool of riparian woodlots, which have components of lower quality (fine and coarse woody debris, sugar maple leaf litter) (Table 4, Appendix 3). Still, litter nutrient storage considerably increases the residence time of nutrients by reducing their mobility in the riparian zone (Hefting et al., 2005). A certain proportion of poplar leaf litter can also be exported by stream water, or is carried by wind into the adjacent cultivated fields. Therefore, we cannot assume that all N and P stocks contained in leaf litter will contribute to the soil N and P pools of the riparian buffer. Water quality concerns may be raised by some, because poplar leaf litter from riparian buffers constitutes a nutrient input to the stream. However, the reintroduction of leaf litter in degraded streams has been found to increase P retention because of increased biofilm activity (Kane et al., 2009), while providing a source of particulate organic matter, which fuels denitrification in stream water (Newcomer et al., 2012). Moreover, allochthonous nutrient inputs derived from litter are the basis of the food web in natural headwater streams of Eastern North America (Webster et al., 1995). Litter inputs are also vital in maintaining complex food web interactions in streams (Wallace et al., 1997).

The potential of non managed (non harvested) herbaceous buffers as a nutrient sink will likely be limited over the years. This is

because a few years after establishment, herbaceous communities reach their equilibrium point (or steady-state), where biomass increments become nil, and nutrient input equals output; allowing for little storage, and high nutrient leaching (Dorizio et al., 2006; Kelly et al., 2007; Vitousek and Reiners, 1975). On the opposite, poplar biomass in the studied buffers is still a growing sink for nutrients, and lower nutrient leaching or movement in soil would be expected from these systems, when compared to non harvested herbaceous buffers, based on the steady state hypothesis (Vitousek and Reiners, 1975). However, mean annual biomass increment and C or nutrient accumulation rates in biomass will level off at some point in time, depending on site fertility and tree spacing (Fang et al., 2007). If not harvested, the poplar buffers will eventually enter a self-thinning process, but living trees will continue to store nutrients in woody biomass, while decaying trees will release nutrients back into the riparian zone, with fine woody debris having much greater decay rates and contributions to N and P cycling than large woody debris (Laiho and Prescott, 1999). While stand productivity and density will decline with the years because of mortality, there are indications that at the individual tree level, large remaining trees will have increasing rates of biomass C storage, and potentially nutrient accumulation (Stephenson et al., 2014). Additionally, in undisturbed conditions, forest ecosystems do not necessarily reach an equilibrium point between assimilation and respiration, so they can continue to store C in living and detrital biomass, and in soils, for long periods of time (Keith et al., 2009; Pregitzer and Euskirchen, 2004; Schulze et al., 2000). However, recent evidence suggests that although accumulation of soil C with forest succession (age) has been found to promote ecosystem N retention, the storage of stable soil N in the O horizon may create a source for chronic dissolved organic N losses to streams (Lewis et al., 2014). The balance between nutrient uptake and storage by living biomass and nutrient inputs from decaying plant material and adjacent agricultural activities, and its effects on soil nutrient losses, should be studied over many years across multiple site conditions and management practices. Such studies would be helpful to determine at which point in time, or in stand development, poplar buffers may reach a steady-state in terms of nutrient

uptake.

Although non harvested herbaceous buffers offer little long-term N and P storage potential (Bedard-Haughn et al., 2005; Kelly et al., 2007; Rätty et al., 2011), numerous studies have found no difference between tree buffers and herbaceous buffers at reducing N loads in agricultural riparian zones (Lyons et al., 2000; Mayer et al., 2007; Sabater et al., 2003). This may be related to the fact that nutrient storage in woody biomass may be relatively low in some mature riparian forest buffers (Peterjohn and Correll, 1984). Still, across several European sites, N retention in riparian forested buffers was higher than in herbaceous buffers because plant production and N uptake were higher in forested buffers (Hefting et al., 2005), a finding that is corroborated by this study. During winter months, a poplar buffer strip was also found to be slightly more effective at reducing groundwater NO₃ load than a herbaceous buffer, despite the absence of N uptake by vegetation (Haycock and Pinay, 1993).

While N and P immobilisation in poplar buffer biomass is an important mechanism of nutrient retention, N and P will not be exported from the riparian zone unless trees are harvested periodically (Kelly et al., 2007). A complete tree harvest (stem + branches) during the dormant season would allow an export of N of 228–844 kg/ha, and an export of P of 25–101 kg/ha for 9-year-old poplars (Table 6). However, a complete harvest would compromise other buffer functions, such as providing habitat for both aquatic and terrestrial biodiversity (Fortier et al., 2011; Simavi, 2012). These trade-offs need to be evaluated carefully when planning a tree harvest in riparian buffers. Rotational or selective harvest may be recommended to maintain a tree structure at the landscape level (Göransson, 1994), while frozen ground harvest would be recommended if heavy machinery is to be used for harvesting, in order to reduce soil compaction and erosion (Abrahamson et al., 1998). Over a 9 year period, harvesting aboveground biomass in the non managed herbaceous buffers of this study (one harvest per year), could also provide similar or even greater N and P export from riparian areas, compared to poplar buffers (Table 6). However, biomass derived from these herbaceous buffers has little economic value, and would require that heavy machinery circulate directly on stream banks, which is not desirable. Stream fencing in pasture sites would also complicate baling operations with a tractor in herbaceous buffers. In comparison, a mechanical tree harvester can easily be positioned metres away from stream banks, or outside fenced riparian zones, and still be capable of harvesting streamside trees.

The exportation potential of poplar buffers that would be completely harvested after 9 years (Table 6) becomes much more marginal when compared to N and P losses to streams of the studied region. In the Beaurivage sub-watershed (Des Appalaches

river watershed, southern Québec), where agricultural land cover is composed of 60% of pastures and hayfields, 23% of cereal fields and 17% of corn fields, nutrient losses to streams were estimated at 27 kg N/ha/yr and 3.2 kg P/ha/yr (Rousseau et al., 2013), or 243 kg N/ha and 28.8 kg P/ha over 9 years. These numbers highlight that low ratios of agricultural area/buffer area will be required to balance N and P losses to streams with N and P exportation in the woody biomass of buffers. Also, a large part of the N and P losses to farm streams in southern Québec occur at snowmelt in spring, and during runoff events caused by late fall rains (Lapp et al., 1998). During these events of high nutrient transport, buffer vegetation is in dormancy, which allows little N and P uptake and storage in plant biomass, although groundwater N removal by denitrification can be important (Haycock and Pinay, 1993). In other words, additional conservation practices should be implemented to complement riparian buffers and increase their effectiveness. These include building soil health (ex: reduce tillage, crop rotation), in-field water control (ex: filter strips, controlled drainage) and below-field water control (ex: constructed wetlands) (Tomer et al., 2013).

Finally, soil nitrate supply rates measured in different riparian vegetation cover types also reveal that allowing livestock access to riparian woodlots may result in very high NO₃ supply rates in soil, as was the case in the white cedar woodlot at Magog (Fig. 2). At this site, the very high NO₃ supply rates observed in the riparian woodlot (280 µg/10 cm²/20 d) contrasts sharply with the low values observed in the nearby herbaceous (19 µg/10 cm²/20 d) and poplar (10 µg/10 cm²/20 d) buffers, which are fenced to prevent livestock access. During hot summer days, we observed on many occasions a herd of cows resting for hours in the shade of the cedar woodlot. Over the years, this riparian woodlot may have received high NO₃ inputs derived from cow urine and feces. Nitrogen load representing 1000 kg N/ha have been measured under cattle urine patches, with NO₃ leaching loss being considerable (Di and Cameron, 2002). Also, the NO₃ enrichment of the Magog riparian woodlot soil by cattle dejections may have been exacerbated by the fact that white cedar is a slow growing tree species, with a marked preference for NH₄ uptake over NO₃ (Farrar, 2006; Gloser et al., 2009).

4.2. Carbon stocks in the different riparian vegetation cover types

In this study, biomass C stocks ranged from 49 to 160 t/ha in natural woodlots, 33–110 t/ha in hybrid poplar buffers, and only 3–4 t/ha in herbaceous buffers (Fig. 1). These field measurements are within the range of published biomass C stocks for different agricultural land uses in Canada, including poplar plantations and farm woodlots (Arevalo et al., 2009). Our biomass C stock estimates for riparian woodlots also fall in the range of mean biomass C stock estimates for managed forests of the Mixedwood plains ecozone (Stinson et al., 2011). Furthermore, our belowground (root) biomass C stock amounts for poplar buffers (4.8–13 t/ha) and riparian woodlots (5.2–36.8 t/ha) (Table 3) are in the same order of magnitude than national scale estimates for managed forests of Eastern Canada, which are 10–17.5 t/ha (Smyth et al., 2013).

Results from this study put in perspective the high potential of hybrid poplar riparian buffers to increase C storage within a decade. Site level comparisons between agricultural buffer types suggest that 9-year-old poplar buffers store 9–31 times more biomass C than herbaceous buffers (Fig. 1). On a mean annual basis, planting poplar buffers in replacement of non managed herbaceous buffer could increase biomass C storage by 3.2–11.9 t/ha/yr (Table 5). Biomass C stocks of poplar buffers were in the range of what was observed in most riparian woodlots (Fig. 1), which suggest that planting poplar buffers in agricultural landscapes can accelerate the

Table 6
Potential C, N and P stock exportations for two types of riparian buffers after 9 years. These estimates are based on a single dormant season harvest of poplar above-ground woody biomass (branches + stems) at the end of the 9th growing season, and the total of 9 harvests (one per year) of herbaceous vegetation in herbaceous buffers in late July.

Vegetation cover	Site	Exportable		
		C (t/ha)	N (kg/ha)	P (kg/ha)
Hybrid poplar buffer	Brompton	90.5	844	101
Hybrid poplar buffer	Magog	24.1	228	25
Hybrid poplar buffer	Roxton	47.8	422	48
Hybrid poplar buffer	St-Isidore	55.8	548	53
Herbaceous buffer	Brompton	20.1	836	179
Herbaceous buffer	Magog	20.0	735	101
Herbaceous buffer	Roxton	17.3	812	113
Herbaceous buffer	St-Isidore	25.9	867	201

rate of C storage compared to natural succession. In fact, abandoned field succession studies suggest that after 50 years following abandonment, tree cover is still very low (<15% of total plant cover), even if those old fields were bordered by woodlots (Inouye et al., 1987; Maycock and Guzikowa, 1984). Therefore, under natural succession, it may take several decades, or even a century, to see C stocks in herbaceous buffers (left to transform through succession into natural tree buffers) restored to levels that are found in natural riparian woodlots. This is especially true when seed sources for forest trees are distant from buffer zones, as it is often the case in agricultural landscapes with low remaining forest cover. But, while biomass C storage rates are generally much higher in afforested hybrid poplars, compared to other temperate tree species (Arevalo et al., 2009; Fang et al., 2007), these stands are also highly vulnerable to pest outbreaks and climatic disturbances (Dickmann, 2001). This makes poplar buffers a less stable C stock over time compared to more diversified and resilient natural riparian woodlots. In that perspective, the best usage of poplar buffers, in a global change mitigation strategy, may be for bioenergy production, which could contribute to fossil fuel displacement, or for the production of solid wood products, which provide long-term off-site C storage. Alternatively, poplar buffers could be managed as nurse stands or as a succession catalysts for slower growing and more shade-tolerant native species, whether under-planted or naturally regenerated (Boothroyd-Roberts et al., 2013a; Gardiner et al., 2004). Such a strategy would accelerate the rebuilding of a diversified biomass C stock in a multi-layered or multi-aged stand structure, which could provide greater biomass C storage over time, compared to even-aged stands (Keith et al., 2009).

Replacing herbaceous buffers by poplar buffers managed for intensive biomass or wood production could also reduce the need for fuel wood or timber harvest in farm woodlots, creating potential local opportunities for forest conservation or extensive management. It is very important to protect remnant natural riparian forest patches, as C reservoirs, especially older ones, given the relatively high amount of C they are storing in different biomass compartments (Fig. 1), and in the soil (Fortier et al., 2013b). As argued by McKinley et al. (2011), avoiding deforestation should receive high priority as policy considerations for C balance management in North America. Allowing existing riparian forests to mature would also be a good strategy to increase C stocks along farm streams (Rheinhardt et al., 2012), given that woodlots composed of late successional species (white cedar, sugar maple and hemlock) contained 2 to 3 times more biomass C stored than in the grey birch woodlot (Fig. 1). These observations are consistent with the general trend of C storage increase as forests age (Alexandrov, 2007; Post and Kwon, 2000; Pregitzer and Euskirchen, 2004).

But beyond avoiding further deforestation, afforestation or agroforestry projects that provide multiple co-benefits and low trade-offs should be strongly promoted for increasing C storage (McKinley et al., 2011). Along this perspective, replacing widespread non managed herbaceous buffers by hybrid poplar buffers, that require no additional nutrient inputs to sustain high biomass yield (Fortier et al., 2013a), should be also seen as a valuable C storage strategy in agricultural landscapes. This replacement would avoid displacing agriculture for afforestation or energy crop production, which could lead to deforestation elsewhere and negate C benefits, (Melillo et al., 2009), as well as reduce food production and security (Campbell et al., 2008). Besides, afforested poplar buffers would provide additional local benefits such as habitat for native forest species, nutrient storage, hydrological control, and lower stream water temperature on small streams (Boothroyd-Roberts et al., 2013a,b; Perry et al., 2001; Updegraff et al., 2004). Still, the C balance of different management scenarios (ex: complete harvest, partial harvest or use as nurse stand) should be fully

investigated for hybrid poplar riparian buffers; and the fate of C in the end product (bioenergy, pulp, solid wood products, etc.) should be integrated as part of the C budget.

Many studies use a C to biomass ratio of 50% to estimate C stocks in different land uses of agricultural landscapes, hybrid poplar plantations and adjacent riparian vegetation cover types (Arevalo et al., 2009; Rheinhardt et al., 2012; Zabek and Prescott, 2006). This practice is in accordance with the Good Practice Guidance of Intergovernmental Panel on Climate Change (2003). However, for the different biomass compartments sampled in this study, C concentration was always below 50% of biomass values (Appendices 1–3). Using a C to biomass ratio of 50% in this study would have caused an overestimation of C stocks in biomass ranging from 7 to 12% in natural riparian woodlots, 8–9% in poplar buffers, and 18–24% in herbaceous buffers. Consequently, C concentrations in biomass compartments should be ideally measured because they can range between 43 and 56% in tree branches, 40–61% in stem wood, 36–43% in fine roots, for different tree species around the world (West, 2009). For native trees of the studied region, C concentration in stem wood is less variable (46–53%) (Lamloom and Savidge, 2003), but still important.

Additional belowground C, N and P stocks could have been added to the poplar buffers if the lateral roots that have colonised the adjacent pastures or cultivated fields could have been accounted for. The same could be said about some roots that were observed below 60 cm of soil depth, and about adventitious poplar roots that were observed growing directly in stream water at some study sites. However, this additional root biomass has not been considered in this study, due to time and logistic limitations, although it may play a key role for nutrient pollution interception.

5. Conclusion

In the agricultural landscapes of southern Québec, most farm streams are bordered by narrow herbaceous buffers that are non managed, allowing for little long-term C and nutrient storage, despite the relatively high nutrient load they may receive annually from adjacent cultivated lands. Over a 9 year period, we found that replacing those herbaceous buffers by hybrid poplar buffers could increase C, N and P storage in biomass by 29–107 t/ha, 284–1120 kg/ha, and 29–141 kg/ha respectively, while substantially reducing NO₃ and P supply rates in riparian soils, at least during the growing season. The biomass C storage value of older natural riparian woodlots was also relatively high, with up to 160 t C/ha.

Acknowledgements

We gratefully acknowledge funding received from Agriculture and Agri-Food Canada (Agricultural Greenhouse Gas Program) and the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) (Programme de Soutien à l'Innovation en Agro-alimentaire) and the Ministère des Ressources Naturelles du Québec (MRN). We also acknowledge Dr. R. Bradley and Dr. W. Parsons (Université de Sherbrooke) for doing the C and N analyses. We are very grateful to the landowners (M. Beaugard, A. Doyon, J. Lamontagne, M. Richer) who have generously welcomed us on their farms and made this research project possible. We also wish to thank H. Isbrucker for providing us with a large amount of space for sample storage and preparation. J. Lemelin, K. Boothroyd-Roberts and M.-A. Pétrin are thanked for their exceptional assistance with field work. A post-doctoral fellowship from the Fiducie de Recherche sur la Forêt des Cantons-de-l'Est to J. Fortier is gratefully acknowledged. Finally, we wish to thank three anonymous reviewers, whose positive and very constructive comments

have significantly contributed to the improvement of this manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jenvman.2015.02.039>.

References

- Abrahamson, L.P., Robison, D.J., Volk, T.A., White, E.H., Neuhauser, E.F., Benjamin, W.H., Peterson, J.M., 1998. Sustainability and environmental issues associated with willow bioenergy development in New York (U.S.A.). *Biomass Bioenergy* 15, 17–22.
- Alexandrov, G., 2007. Carbon stock growth in a forest stand: the power of age. *Carbon Balance Manag.* 2, 4.
- AOAC, 1999. Association of Official Analytical Chemists (AOAC) Official Methods. Method 984.27: Calcium, Copper, Iron, Magnesium, Manganese, Phosphorus, Potassium, Sodium and Zinc in Infant Formula – Inductively Coupled Plasma Emission Spectroscopic, sixteenth ed. AOAC International.
- Arevalo, C.B.M., Bhatti, J.S., Chang, S.X., Sidders, D., 2009. Ecosystem carbon stocks and distribution under different land-uses in north central Alberta, Canada. *For. Ecol. Manag.* 257, 1776–1785.
- Aye, T.M., Nguyen, M.L., Bolan, N.S., Hedley, M.J., 2006. Phosphorus in soils of riparian and non-riparian wetland and buffer strips in the Waikato area, New Zealand. *N. Z. J. Agric. Res.* 49, 349–358.
- Bedard-Haughn, A., Tate, K.W., van Kessel, C., 2005. Quantifying the impact of regular cutting on vegetative buffer efficacy for nitrogen-15 sequestration. *J. Environ. Qual.* 34, 1651–1664.
- Boothroyd-Roberts, K., Gagnon, D., Truax, B., 2013a. Can hybrid poplar plantations accelerate the restoration of forest understorey attributes on abandoned fields? *For. Ecol. Manag.* 287, 77–89.
- Boothroyd-Roberts, K., Gagnon, D., Truax, B., 2013b. Hybrid poplar plantations are suitable habitat for reintroduced forest herbs with conservation status. *SpringerPlus* 2, 1–13.
- Boutin, C., Jobin, B., Bélanger, L., 2003. Importance of riparian habitats to flora conservation in farming landscapes of southern Québec, Canada. *Agric. Ecosyst. Environ.* 94, 73–87.
- Bradshaw, H.D., Ceulemans, R., Davis, J., Stettler, R., 2000. Emerging model systems in plant biology: Poplar (*Populus*) as a model forest tree. *J. Plant Growth Reg.* 19, 306–313.
- Brockerhoff, E., Jactel, H., Parrotta, J., Quine, C., Sayer, J., 2008. Plantation forests and biodiversity: oxymoron or opportunity? *Biodivers. Conserv.* 17, 925–951.
- Buell, M.F., Buell, H.F., 1959. Aspen invasion of prairie. *Bull. Torrey Botanical Club* 86, 264–265.
- Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The global potential of bioenergy on abandoned agriculture lands. *Environ. Sci. Technol.* 42, 5791–5794.
- Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* 8, 559–568.
- Chazdon, R.L., 2008. Beyond deforestation: restoring forests and ecosystem services on degraded lands. *Science* 320, 1458–1460.
- Di, H.J., Cameron, K.C., 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutr. Cycl. Agroecosyst.* 64, 237–256.
- Dickmann, D.I., 2001. An overview of the genus *Populus*. In: Dickmann, D.I., Isebrands, J.G., Eckenwalder, J.E., Richardson, J. (Eds.), *Poplar Culture in North America*. Part A. NRC Research Press, National Research Council of Canada, Ottawa, ON, pp. 1–42 (chapter 1).
- Dickmann, D.I., Kuzovkina, Y.A., 2008. *Poplars and Willows of the World, with Emphasis on Silviculturally Important Species*. Rome, Italy: FAO Forest Management Division Working Paper IPC/9-2.
- Dorioz, J.M., Wang, D., Pouléard, J., Trévisan, D., 2006. The effect of grass buffer strips on phosphorus dynamics – a critical review and synthesis as a basis for application in agricultural landscapes in France. *Agric. Ecosyst. Environ.* 117, 4–21.
- Dosskey, M.G., Vidon, P., Gurwick, N.P., Allan, C.J., Duval, T.P., Lowrance, R., 2010. The role of riparian vegetation in protecting and improving chemical water quality in streams. *JAWRA* 46, 261–277.
- Fang, S., Xue, J., Tang, L., 2007. Biomass production and carbon sequestration potential in poplar plantations with different management patterns. *J. Environ. Manag.* 85, 672–679.
- Farrar, J.L., 2006. *Les arbres du Canada*. Fides et le Service canadien des forêts. Ressources naturelles Canada, St-Laurent, Qc.
- Fortier, J., Gagnon, D., Truax, B., Lambert, F., 2010a. Biomass and volume yield after 6 years in multiclonal hybrid poplar riparian buffer strips. *Biomass Bioenergy* 34, 1028–1040.
- Fortier, J., Gagnon, D., Truax, B., Lambert, F., 2010b. Nutrient accumulation and carbon sequestration in 6 year-old hybrid poplars in multiclonal agricultural riparian buffer strips. *Agric. Ecosyst. Environ.* 137, 276–287.
- Fortier, J., Gagnon, D., Truax, B., Lambert, F., 2011. Understorey plant diversity and biomass in hybrid poplar riparian buffer strips in pastures. *New For.* 42, 241–265.
- Fortier, J., Truax, B., Gagnon, D., Lambert, F., 2012. Hybrid poplar yields in Québec: implications for a sustainable forest zoning management system. *For. Chron.* 88, 391–407.
- Fortier, J., Truax, B., Gagnon, D., Lambert, F., 2013a. Mature hybrid poplar riparian buffers along farm streams produce high yields in response to soil fertility assessed using three methods. *Sustainability* 5, 1893–1916.
- Fortier, J., Truax, B., Gagnon, D., Lambert, F., 2013b. Root biomass and soil carbon distribution in hybrid poplar riparian buffers, herbaceous riparian buffers and natural riparian woodlots on farmland. *SpringerPlus* 2, 539.
- Gardiner, E.S., Stanturf, J.A., Schweitzer, C.J., 2004. An afforestation system for restoring bottomland hardwood forests: biomass accumulation of nuttall oak seedlings interplanted beneath eastern cottonwood. *Rest. Ecol.* 12, 525–532.
- Gloser, V., Sedláček, P., Gloser, J., 2009. Consequences of nitrogen deficiency induced by low external N concentration and by patchy N supply in *Picea abies* and *Thuja occidentalis*. *Trees* 23, 1–9.
- Göransson, G., 1994. Bird fauna of cultivated energy shrub forests at different heights. *Biomass Bioenergy* 6, 49–52.
- Harmon, M.E., Woodall, C.W., Fasth, B., Sexton, J., 2008. *Woody Detritus Density and Density Reduction Factors for Tree Species in the United States: a Synthesis*. United States Department of Agriculture, Forest Service, Northern Research Station. General Technical Report NRS-29, Newtown Square, PA.
- Haycock, N.E., Pinay, G., 1993. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during the winter. *J. Environ. Qual.* 22, 273–278.
- Hefting, M.M., Clement, J.-C., Bienkowski, P., Dowrick, D., Guenat, C., Butturini, A., Topa, S., Pinay, G., Verhoeven, J.T.A., 2005. The role of vegetation and litter in the nitrogen dynamics of riparian buffer zones in Europe. *Ecol. Eng.* 24, 465–482.
- Hill, A.R., 1996. Nitrate removal in stream riparian zones. *J. Environ. Qual.* 25, 743–755.
- Hooker, T.D., Compton, J.E., 2003. Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment. *Ecol. Appl.* 13, 299–313.
- Inouye, R.S., Huntly, N.J., Tilman, D., Tester, J.R., Stillwell, M., Zinnel, K.C., 1987. Old-field succession on a Minnesota Sand Plain. *Ecology* 68, 12–26.
- Intergovernmental Panel on Climate Change, 2003. *Good Practice Guidance for Land-use, Land-use Change and Forestry*. Institute for Global Environmental Strategies, Hayama, Japan.
- Jarrell, W.M., Beverly, R.B., 1981. The dilution effect in plant nutrition studies. *Adv. Agron.* 34, 197–224.
- Jobin, B., Bélanger, L., Boutin, C., Maisonneuve, C., 2004. Conservation value of agricultural riparian strips in the Boyer River watershed, Québec (Canada). *Agric. Ecosyst. Environ.* 103, 413–423.
- Johnson, D.W., Glass, D.W., Murphy, J.D., Stein, C.M., Miller, W.W., 2010. Nutrient hot spots in some sierra Nevada forest soils. *Biogeochem* 101, 93–103.
- Kane, T.A., Justin, D.B., George, G.G., 2009. Rehabilitation of stream ecosystem functions through the reintroduction of coarse particulate organic matter. *Rest. Ecol.* 17, 97–106.
- Keith, H., Mackey, B.G., Lindenmayer, D.B., 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proc. Natl. Acad. Sci.* 106, 11635–11640.
- Kelly, J., Kovar, J., Sokolowsky, R., Moorman, T., 2007. Phosphorus uptake during four years by different vegetative cover types in a riparian buffer. *Nutr. Cycl. Agroecosyst.* 78, 239–251.
- Kronvang, B., Grant, R., Larsen, S., Svendsen, L., Kristensen, P., 1995. Non-point-source nutrient losses to the aquatic environment in Denmark: impact of agriculture. *Mar. Freshw. Res.* 46, 167–177.
- Laiho, R., Prescott, C.E., 1999. The contribution of coarse woody debris to carbon, nitrogen, and phosphorus cycles in three Rocky Mountain coniferous forests. *Can. J. For. Res.* 29, 1592–1603.
- Lal, R., Delgado, J.A., Groffman, P.M., Millar, N., Dell, C., Rotz, A., 2011. Management to mitigate and adapt to climate change. *J. Soil Water Conserv.* 66, 276–285.
- Lamloom, S.H., Savidge, R.A., 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. *Biomass Bioenergy* 25, 381–388.
- Lapp, P., Madramootoo, C.A., Enright, P., Papineau, F., Perrone, J., 1998. Water quality of an intensive agricultural watershed in Québec. *JAWRA* 34, 427–437.
- Lewis, D.B., Castellano, M.J., Kaye, J.P., 2014. Forest succession, soil carbon accumulation, and rapid nitrogen storage in poorly remineralized soil organic matter. *Ecology* 95, 2687–2693.
- Lowrance, R., 1992. Groundwater nitrate and denitrification in a Coastal Plain riparian forest. *J. Environ. Qual.* 21, 401–405.
- Lowrance, R., Altier, L.S., Newbold, J.D., Schnabel, R.R., Groffman, P.M., Denver, J.M., Correll, D.L., Gilliam, J.W., Robinson, J.L., Brinsfield, R.B., Staver, K.W., Lucas, W., Todd, A.H., 1997. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. *Environ. Manag.* 21, 687–712.
- Lyons, J., Thimble, S.W., Paine, L.K., 2000. Grass versus trees: managing riparian areas to benefit streams of central North America. *JAWRA* 36, 919–930.
- Maycock, P.F., Guzikowa, M., 1984. Flora and vegetation of an old field community at Erindale, southern Ontario. *Can. J. Bot.* 62, 2193–2207.
- Mayer, P.M., Reynolds, S.K., Marshall, M., Canfield, T.J., 2007. Meta-analysis of nitrogen removal in riparian buffers. *J. Environ. Qual.* 36, 1172–1180.
- McClain, M.E., Boyer, E.W., Dent, C.L., Gergel, S.E., Grimm, N.B., Groffman, P.M., Hart, S.C., Harvey, J.W., Johnston, C.A., Mayorga, E., McDowell, W.H., Pinay, G., 2003. Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosyst.* 6, 301–312.

- McKinley, D.C., Ryan, M.G., Birdsey, R.A., Giardina, C.P., Harmon, M.E., Heath, L.S., Houghton, R.A., Jackson, R.B., Morrison, J.F., Murray, B.C., Pataki, D.E., Skog, K.E., 2011. A synthesis of current knowledge on forests and carbon storage in the United States. *Ecol. Appl.* 21, 1902–1924.
- Melillo, J.M., Reilly, J.M., Kicklighter, D.W., Gurgel, A.C., Cronin, T.W., Paltsev, S., Felzer, B.S., Wang, X., Sokolov, A.P., Schlosser, C.A., 2009. Indirect emissions from biofuels: how important? *Science* 326, 1397–1399.
- Moliner, J., Pozo, J., 2006. Organic matter, nitrogen and phosphorus fluxes associated with leaf litter in two small streams with different riparian vegetation: a budget approach. *Arch. für Hydrobiol.* 166, 363–385.
- Montagnini, F., Nair, P.F.K., 2004. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. *Agrofor. Syst.* 61, 281–295.
- Mourelle, C., Kellman, M., Kwon, L., 2001. Light occlusion at forest edges: an analysis of tree architectural characteristics. *For. Ecol. Manag.* 154, 179–192.
- Newcomer, T.A., Kaushal, S.S., Mayer, P.M., Shields, A.R., Canuel, E.A., Groffman, P.M., Gold, A.J., 2012. Influence of natural and novel organic carbon sources on denitrification in forest, degraded urban, and restored streams. *Ecol. Monogr.* 82, 449–466.
- Perry, C.H., Miller, R.C., Brooks, K.N., 2001. Impacts of short-rotation hybrid poplar plantations on regional water yield. *For. Ecol. Manag.* 143, 143–151.
- Peterjohn, W.T., Correll, D.L., 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. *Ecology* 65, 1466–1475.
- Post, W., Kwon, K., 2000. Soil carbon sequestration and land-use change: processes and potential. *Glob. Change Biol.* 6, 317–327.
- Pregitzer, K.S., Euskirchen, E.S., 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. *Glob. Change Biol.* 10, 2052–2077.
- Qian, P., Schoenau, J.J., Huang, W.Z., 1992. Use of ion exchange membranes in routine soil testing. *Comm. Soil S. C. Plant Anal.* 23, 1791–1804.
- Räty, M., Uusi-Kämpä, J., Yli-Halla, M., Rasa, K., Pietola, L., 2011. Phosphorus and nitrogen cycles in the vegetation of differently managed buffer zones. *Nutr. Cycl. Agroecosyst.* 86, 121–132.
- Rheinhardt, R., Brinson, M., Meyer, G., Miller, K., 2012. Carbon storage of headwater riparian zones in an agricultural landscape. *Carbon Balance Manag.* 7, 4.
- Righelato, R., Spracklen, D.V., 2007. Carbon mitigation by biofuels or by saving and restoring forests? *Science* 317, 902.
- Rousseau, A.N., Savary, S., Hallema, D.W., Gumiere, S.J., Foulon, É., 2013. Modeling the effects of agricultural BMPs on sediments, nutrients, and water quality of the Beauvive River watershed (Quebec, Canada). *Can. Water Resour. J.* 38, 99–120.
- Rouvinen, S., Kuuluvainen, T., Karjalainen, L., 2002. Coarse woody debris in old *Pinus sylvestris* dominated forests along a geographic and human impact gradient in boreal Fennoscandia. *Can. J. For. Res.* 32, 2184–2200.
- Sabater, S., Butturini, A., Clement, J.-C., Burt, T., Dowrick, D., Hefting, M., Matre, V., Pinay, G., Postolache, C., Rzepecki, M., Sabater, F., 2003. Nitrogen removal by riparian buffers along a European climatic gradient: patterns and factors of variation. *Ecosyst.* 6, 0020–0030.
- Schulze, E.D., Wirth, C., Heimann, M., 2000. Managing forests after Kyoto. *Sci. Wash.* 289, 2058–2059.
- Simavi, M.A., 2012. Effet de plantations de bandes riveraines d'arbres sur l'abondance et la répartition de la faune aquatique dans des ruisseaux dégradés de milieux agricoles dans les Cantons-de-l'Est (M.Sc. thesis). Université du Québec à Montréal, Montréal (QC), Canada, p. 89.
- Smyth, C.E., Kurz, W.A., Neilson, E.T., Stinson, G., 2013. National-scale estimates of forest root biomass carbon stocks and associated carbon fluxes in Canada. *Glob. Biogeochem. Cycles* 27, 1262–1273.
- Stephenson, N.L., Das, A.J., Condit, R., Russo, S.E., Baker, P.J., Beckman, N.G., Coomes, D.A., Lines, E.R., Morris, W.K., Ruger, N., Alvarez, E., Blundo, C., Bunyavejchewin, S., Chuyong, G., Davies, S.J., Duque, A., Ewango, C.N., Flores, O., Franklin, J.F., Grau, H.R., Hao, Z., Harmon, M.E., Hubbell, S.P., Kenfack, D., Lin, Y., Makana, J.R., Malizia, A., Malizia, L.R., Pabst, R.J., Pongpattananurak, N., Su, S.H., Sun, I.F., Tan, S., Thomas, D., van Mantgem, P.J., Wang, X., Wiser, S.K., Zavala, M.A., 2014. Rate of tree carbon accumulation increases continuously with tree size. *Nature* 507, 90–93.
- Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., Boisvenue, C., Rampley, G.J., Li, Q., White, T.M., Blain, D., 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Glob. Change Biol.* 17, 2227–2244.
- Sweeney, B.W., Bott, T.L., Jackson, J.K., Kaplan, L.A., Newbold, J.D., Standley, L.J., Hession, W.C., Horwitz, R.J., 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *PNAS* 101, 14132–14137.
- Ter-Mikaelian, M.T., Korzukhin, M.D., 1997. Biomass equations for sixty-five North American tree species. *For. Ecol. Manag.* 97, 1–24.
- Tomer, M.D., Porter, S.A., James, D.E., Boomer, K.M.B., Kostel, J.A., McLellan, E., 2013. Combining precision conservation technologies into a flexible framework to facilitate agricultural watershed planning. *J. Soil Water Conserv.* 68, 113A–120A.
- Truax, B., Gagnon, D., Fortier, J., Lambert, F., 2012. Yield in 8 year-old hybrid poplar plantations on abandoned farmland along climatic and soil fertility gradients. *For. Ecol. Manag.* 267, 228–239.
- Tufekcioglu, A., Raich, J.W., Isenhardt, T.M., Schultz, R.C., 2003. Biomass, carbon and nitrogen dynamics of multi-species riparian buffers within an agricultural watershed in Iowa, USA. *Agrofor. Syst.* 57, 187–198.
- Updegraff, K., Baughman, M.J., Taff, S.J., 2004. Environmental benefits of cropland conversion to hybrid poplar: economic and policy considerations. *Biomass Bioenergy* 27, 411–428.
- Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. *Annu. Rev. Environ. Resour.* 37, 195–222.
- Vidon, P., Allan, C., Burns, D., Duval, T.P., Gurwick, N., Inamdar, S., Lowrance, R., Okay, J., Scott, D., Sebestyen, S., 2010. Hot spots and hot moments in riparian zones: potential for improved water quality management. *JAWRA* 46, 278–298.
- Vitousek, P.M., Reiners, W.A., 1975. Ecosystem succession and nutrient retention: a hypothesis. *BioScience* 25, 376–381.
- Wallace, J.B., Eggert, S.L., Meyer, J.L., Webster, J.R., 1997. Multiple trophic levels of a forest stream linked to terrestrial litter inputs. *Science* 277, 102–104.
- Webster, J.R., Wallace, J.B., Benfield, E.F., 1995. Organic processes in streams of the Eastern United States. In: Cushing, C.E., Cummins, K.W., Minshall, G.W. (Eds.), *River and Stream Ecosystems*. Elsevier, New York, NY, pp. 117–188.
- West, P., 2009. *Tree and Forest Measurement*. Springer-Verlag, Berlin Heidelberg, Germany.
- Zabek, L.M., Prescott, C.E., 2006. Biomass equations and carbon content of above-ground leafless biomass of hybrid poplar in Coastal British Columbia. *For. Ecol. Manag.* 223, 291–302.
- Zhou, X., Brandle, J.R., Awada, T.N., Schoeneberger, M.M., Martin, D.L., Xin, Y., Tang, Z., 2011. The use of forest-derived specific gravity for the conversion of volume to biomass for open-grown trees on agricultural land. *Biomass Bioenergy* 35, 1721–1731.