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Article

Mature Hybrid Poplar Riparian Buffers along Farm Streams Produce High Yields in Response to Soil Fertility Assessed Using Three Methods

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Abstract: This study had three main objectives: (1) to evaluate the aboveground biomass and volume yield of three unrelated hybrid poplar clones in 9 year-old riparian buffer strips located on four farms of southern Québec, Canada; (2) to compare yield data at 9 years with previous data (at 6 years); (3) to evaluate how soil fertility, measured using three different soil testing methods (soil nutrient stocks, soil nutrient concentrations, soil nutrient supply rates), is related to yield. Across the four sites, hybrid poplar productivity after 9 years ranged from 116 to 450 m^3ha^{-1}, for stem wood volume, and from 51 to 193 megagrams per hectare (Mg ha^{-1}), for woody dry biomass. High volume and woody dry biomass yields (26.3 to 49.9 $m^3ha^{-1}yr^{-1}$, and 11.4 to 21.4 Mg $ha^{-1}yr^{-1}$) were observed at the three most productive sites. From year 6 to 9, relatively high yield increases (8.9–15.1 $m^3ha^{-1}yr^{-1}$) were observed at all sites, but the productivity gap between the less fertile site and the three other sites was widened. Clone MxB-915311 was the most productive across the four sites, while clone DxN-3570 was the least productive. However, at the most productive site, clone MxB-915311 experienced severe stem and branch breakages. Independently of the soil testing method used, available soil P was always the first soil factor explaining volume yield.

Keywords: agroforestry; afforestation; biomass; wood volume; ion exchange membranes

1. Introduction

Wood and woody biomass production on the farm using natural or planted short-rotation woody crops or coppices in the riparian zone of agroecosystems is an idea gaining acceptance worldwide [1–6]. Within this perspective, streamside plantations and agroforestry systems composed of fast-growing species, such as *Populus* spp. and their hybrids, may be used to create more diversified and resilient farmland ecosystems [3,7,8].

On the one hand, riparian zones are keystone elements for providing ecosystem services (water quality protection, soil stabilization, carbon sequestration, refuges for biodiversity, storm and flood protection, *etc.*) [9–13]. Consequently, in landscapes that have historically been forested, degraded agricultural riparian zones have a high potential for restoring ecosystem services through the establishment of woody vegetation buffers [14–18]. On the other hand, riparian zones in agroecosystems are generally highly productive ecotones because of adjacent agricultural activities, which make them very interesting for the production of woody biomass or solid wood products [1,3]. Producing woody biomass and timber in planted buffer strips might also be a way to partially offset economic losses associated with cropland or pasture conversion to woody vegetation, but also establishment and maintenance costs. This is a major issue for biomass production, particularly in more intensive farming landscapes where land value is high because of its excellent agricultural potential [19]. High crop value, along with the lack of markets that account for ecosystem services, are other factors that contribute to reduce the feasibility of on-farm conservation practices, such as woody riparian buffer implementation [20].

In that context, yield studies in poplar riparian buffer strips are highly needed because of their economic implications, for both landowners and land managers. In the United States, it has been shown that a small yield increase in poplar buffer strips, from 11.2 to 13.4 megagrams per hectare per year (Mg $ha^{-1}yr^{-1}$), could reduce biomass production costs by 10 to 13% [21]. This is because at higher yields fixed costs are spread over more units, while increasing the productivity of the harvesting equipment [21]. At a regional level, enormous yield gains can be made simply by choosing high fertility sites, with a set of productive clones adapted to the local climate [22].

Very few studies have documented the biomass production potential of *Populus* hybrids in agricultural riparian buffer strips [1,2,23]. In a previous study, we observed large yield variations (2–17 Mg $ha^{-1}yr^{-1}$ and 4–40 $m^3ha^{-1}yr^{-1}$) in six year-old hybrid poplar buffer strips, with soil nitrate (NO_3) supply rate being highly correlated to growth [1]. This study also reported important yield variation associated with clone selection across the four study sites (5–11 Mg $ha^{-1}yr^{-1}$ and 14–22 $m^3ha^{-1}yr^{-1}$). These results suggest that site and clone selection are very important to optimize yield in the early stages of buffer strip development. However, yield data in mature poplar riparian buffers strips are unavailable at the moment. Obtaining yield data along the rotation is important to evaluate wood and biomass stocks periodically. In short, site quality, genotype selection, and rotation length are important factors that a landowner should consider to optimize his economic gains from high yielding plantation systems [24].

Wood quality is also an important factor for landowners who wish to commercialize hybrid poplar wood from agricultural riparian buffers. As shown by Johnson and Henri [25], achieving a positive net return for the landowner of hybrid poplar buffers located on a blueberry farm also depends on timber quality, not only on harvested volume. In this perspective, the quantity of high quality timber produced can be enhanced by clone selection, by tree pruning, as well as by managing hybrid poplars on longer rotations [26–29]. Therefore, it is important to identify hybrid poplar clones that are more productive, but also the clones that have a suitable architecture and sufficient longevity for the production of sawlogs and veneer.

Making yields of hybrid poplars in riparian buffers more predictable at the farm scale is also imperative in order to properly inform landowners about the potential of their site for biomass or timber production. A better understanding of plant-soil relationships is needed since hybrid poplars of different parentages are highly sensitive to site fertility in both riparian and upland sites in agricultural landscapes of southern Québec [1,22]. Different soil testing methods are currently used by agronomists, foresters, and environmental consultants. For example, soil nutrient stocks, soil nutrient concentrations and nutrient supply rates are frequently used in routine soil testing [30–32]. Yet, no study has compared the ability of these methods to assess site quality for agroforestry systems, such as hybrid poplar riparian buffer strips. Are these methods comparable, and what are the advantages and disadvantages of these methods?

The first objective of this study was to evaluate the biomass and volume yield of three unrelated hybrid poplar clones in nine year-old hybrid poplar riparian buffer strips located on four farms of southern Québec, Canada. The second objective was to compare these yield data with previous data (at 6 years) to identify the potential yield increases with longer rotation length. The third objective was to evaluate how soil fertility, measured using three different soil-testing methods (soil nutrient stocks, soil nutrient concentrations and soil nutrient supply rates), is related to hybrid poplar yield.

In this study, the term "woody biomass" represents the sum of stems and branches on a per hectare basis, which is the total harvestable aboveground dry woody biomass. The term «volume» refers to the stem wood volume outside the bark. In this study, one hectare of riparian buffer strip has the dimensions: four and a half meters wide on both stream banks along 1.11 km of stream.

2. Materials and Methods

2.1. Study Sites and Experimental Design

The four riparian buffer study sites (Bromptonville, Magog, Roxton Falls and St-Isidore-de-Clifton) are located in southern Québec, eastern Canada. At each site, the hybrid poplar riparian buffer borders 90 m of stream length on both stream banks and has a width of 4.5 m (3 hybrid poplar rows) on each stream bank. Stem density at planting was 2222 stems ha^{-1} (1.5 × 3 m spacing), but it ranges from 1500 to 1930 stems ha^{-1} after nine years because of some tree mortality and the harvest of one hybrid poplar per plot in 2008. Hybrid poplar riparian buffer strips had received very minimal silvicultural treatments; there was no site/soil preparation and there was a single local (1 m^2/tree) herbicide application early during the first growing season. Additional information on planting stock, buffer design, management, and site characteristics is presented in previous studies [1,14,15] and is briefly summarized in Table 1. From the five hybrid poplar clones that were initially planted in the buffer strips, three were retained for this study: (1) *Populus deltoides* × *nigra* (DxN-3570), originating from Belgium, (2) *P. canadensis* × *maximowiczii* (DNxM-915508), originating from Québec, and (3) *P. maximowiczii* × *balsamifera* (MxB-915311), also originating from Québec. These clones have been selected for their superior growth and disease resistance / tolerance in a wood production perspective [33]. The two other clones that are in the experimental design, *P. nigra* × *P. maximoviczii* (NxM-3729) and *P. trichocarpa* × *P. deltoides* (TxD-3230) have been discarded as they are no longer recommended for the study area (southern Québec) because of disease problems [33].

A randomized block design was used at each of the four sites, with four blocks and three hybrid poplar clones for a total of 48 experimental plots (four sites × three clones × four blocks/site). Dimensions of a plot are 4.5 m wide per 9 m of stream length (40.5 m^2/plot). Initially each plot contained nine trees of a single clone. This design allowed us to test Site and Clone effects (main effects) as well as Site × Clone interaction, a common design used for crop cultivar evaluation [34].

Table 1. Site characteristics of the agricultural land bordering the hybrid poplar riparian buffer strips.

Sites	Land use	Yearly fertilization	Fertilization and lime addition (every 5 years)	Cattle density (per ha)	Elevation (m)
Bromptonville	Pasture	Cattle manure	None	0.6	140
Magog	Pasture	None	None	0.2	208
Roxton Falls	Hayfield	None	None	-	147
St-Isidore-de-Clifton	Pasture	Cattle manure	N (18 kg ha^{-1}) + lime (800 kg ha^{-1})	0.5	360

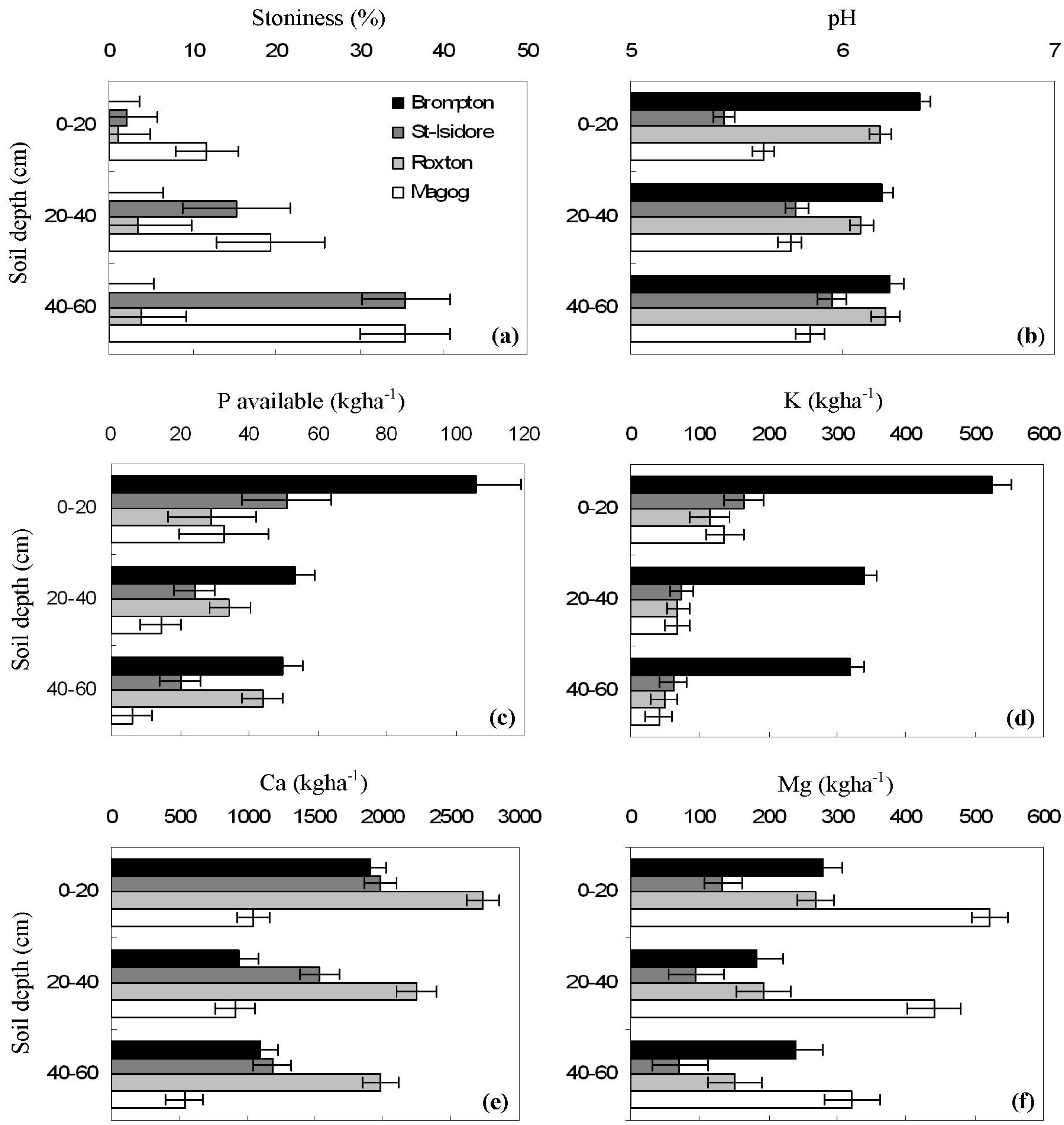
2.2. Soil Characteristics, Nutrient Stocks and Supply Rates

In each plot (n = 48), soil pits (50 × 50 cm by 60 cm depth) were excavated. During the month of July 2011, soil samples were collected with a soil corer (diameter = 5.3 cm, length = 10 cm) from pit walls at three different depth ranges, 0–20, 20–40 and 40–60 cm. In each plot and for each depth range, a composite soil sample was obtained by combining two soil cores per depth range, for a total of 144 soil samples.

Soil samples were air dried and sieved (2 mm). Soil pH and concentrations of Ca, Mg, K, and available P were determined by the Agridirect Inc. soil analysis lab in Longueuil (Québec). Methods used are those recommended by the Conseil des productions végétales du Québec [32]. The determination of soil pH was made using a 2:1 ratio of water to soil. Calcium, Mg, K and P were extracted using the Mehlich III method [35] and determined using ICP spectrophotometry [36]. Soil nitrogen forms (NO_3 and NH_4) were not measured because it was not logistically and economically possible to proceed to N-form extraction on fresh soils or to dry soil immediately after sampling as recommended by Westfall *et al.* [37].

Soil bulk density was determined by drying sieved soil samples at 105 °C and dividing the fine earth (<2 mm particle size fraction) soil dry mass by the volume of the soil core [38]. Because bulk density measured with soil cores does not account for large rock fragments in the soil [39], stoniness was assessed visually, by at least two persons, from the soil pit excavations. For each sampling depth, stones that were removed by excavation were replaced in the pit to estimate pit volume (%) that was occupied by stones. Nutrient stocks in the fine earth fraction of the three soil depth ranges sampled were calculated on a per hectare basis by multiplying nutrient concentrations with soil mass contained in a given volume, taking into account soil bulk density and stoniness (stone volume subtracted). Soil nutrient stocks, pH and stoniness data are presented in Figure 1.

Figure 1. Soil characteristics for three soil depth ranges (0–20, 20–40 and 40–60 cm) at the four hybrid poplar riparian buffer sites: (**a**) Stoniness (%), (**b**) soil pH, (**c**) available P stocks (kg ha^{-1}), (**d**) K stocks (kg ha^{-1}), (**e**) Ca stocks (kg ha^{-1}) and (**f**) Mg stocks (kg ha^{-1}). For each soil characteristic at each depth range, Site effect is significant at $p < 0.05$, except for stoniness at 0–20 and 20–40 cm depth ranges, which is not significant. Bars represent standard error (SE).



Nutrient supply rates in the entire experimental design were determined using Plant Root Simulator (PRS^{TM}-Probes) technology from Western Ag Innovations Inc. Saskatoon, Canada. The PRS-probes consist of an ion exchange membrane encapsulated in a thin plastic probe, which is inserted into the ground with little disturbance of soil structure. 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 = 48) 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 analysis (NO_3, NH_4, P, K, Ca, Mg). Composite samples were made in each plot by combining the four pairs of probes. Probe supply rates are reported as µg of nutrient 10 cm^{-2} 20d^{-1}. Nutrient supply rates measured at each site are presented in Table 2.

Table 2. Nutrient supply rate (µg10cm^{-2} 20d^{-1}) measured in August 2011 in the soil of the hybrid poplar riparian buffer sites.

Sites	NO_3	NH_4	P	Ca	K	Mg
Bromptonville	37.2	5.06	5.28	748	519	172
St-Isidore-de-Clifton	52.4	5.23	2.94	1014	108	135
Roxton Falls	9.2	4.05	3.18	1331	70	189
Magog	10.3	6.28	1.85	644	60	524
SE	8.1	0.46	0.70	46	26	21
$p<$	0.01	0.05	0.05	0.001	0.001	0.001

2.3. Regression Procedures and Yield Measurements

As in our previous yield studies [1,22], we used a model-based sampling approach [40], by developing new allometric relationships for each hybrid poplar clone to assess yields. The choice of this sampling approach was motivated by the fact that the use of allometric relationships developed from sites outside of study locations, and thus reflecting the conditions of the sites on which they were developed, may generate very large errors in hybrid poplar biomass or volume estimates [41]. Furthermore, since forest grown trees have different biomass allocation patterns than trees grown in more open agroforestry systems, it is imperative to develop species specific or clone specific allometric equations for different agroforestry practices [42].

At the end of the ninth growing season (late October 2011 to early November 2011), we selected one representative hybrid poplar in each experimental plot, for a total 48 trees. In general, the tree that had a diameter at breast height (DBH) closest to the mean DBH of the trees in the plot was selected. However, in plots where the largest individual poplar (over all sites) of each clone occurred, this larger tree was selected in order to have the full range of large diameter trees in the hybrid poplar population studied [43]. Selected trees were cut at the ground level and aboveground compartments (branches and stem) were separated and weighed fresh using a tripod scale. Sub-samples from stem and branches were immediately weighed in the field and taken back to the lab for determining dry weight.

To calculate stem volume (outside of the bark) of the 48 sampled trees, the following measurements were taken outside of the bark: ground level diameter, DBH, length from the tree base to 20 cm diameter, length from the tree base to 10 cm diameter, and length from tree base to 3 cm diameter. For large trees (DBH > 20 cm), stem volume was calculated for four sections of the stem: (1) tree base diameter to DBH, (2) DBH to 20 cm diameter (3) 20 cm to 10 cm diameter, and (4) 10 cm diameter to

3 cm diameter. For medium size trees (DBH = 10-20 cm), stem volume was calculated for three sections of the stem: (1) tree base diameter to DBH, (2) DBH to 10 cm diameter, and (3) 10 cm diameter to 3 cm diameter. For smaller trees (DBH ≤ 10 cm) volume was calculated for two sections of the stem: (1) tree base diameter to DBH and (2) DBH to 3 cm diameter. Volumes of different stem sections were then summed to obtain total stem volume for each of the sampled hybrid poplars. Volume calculations were made using the following equation [44]:

$$V = \pi/12(D_1^2+D_2^2+D_1D_2)\,L \qquad (1)$$

Where, V is the volume of a stem section, D_1 is the base diameter of the stem section, D_2 is the diameter at the top of the stem section, and L is the length of the stem section.

With data from the stems and branches of 16 trees per clone, clone specific allometric relationships for volume and biomass *versus* DBH were developed, with DBH being the predictor variable (*X*) and biomass (stem or branches) and stem volume being the response variable (*Y*) (Figure 2, Table 3). Residuals were plotted and compared to a normal distribution in order to determine the goodness-of-fit according to the Shapiro-Wilk *W* test. Regression model selection was based on both the fit (R^2) of the regression and the goodness of fit (*W*). Therefore, when the fit of two different models was comparable for a given clone, the model with the highest normality in the distribution of residuals was chosen. These allometric relationships were then used to estimate woody biomass and stem volume of each single tree in the entire experimental design. The DBH measurements were made at the end of the ninth growing season, from late October to early November 2011.

At the Bromptonville site, some trees of clone MxB-915311 had broken at the end of the eighth and during the ninth growing seasons and were harvested by the landowner. The volume and woody biomass of those trees was considered in our woody biomass and volume calculations. To estimate the woody biomass and stem volume of those harvested trees, we developed a relationship between the ground level diameter (GLD) and the DBH of clone MxB-915311, to obtain a DBH value:

$$DBH = 0.7959\,(GLD) - 0.091 \qquad R^2 = 0.97 \qquad (2)$$

With this calculated DBH value, we estimated stem volume and branch and stem biomass with the allometric relationships previously described.

Figure 2. Allometric relationships between (**a**) diameter at breast height (DBH) (cm) and stem volume (dcm^3), (**b**) DBH and stem dry biomass (kg) and (**c**) DBH and branch dry biomass for the three hybrid poplar clones: MxB-915311 (dotted line), DNxM-915508 (thin solid line) and DxN-3570 (thick solid line).

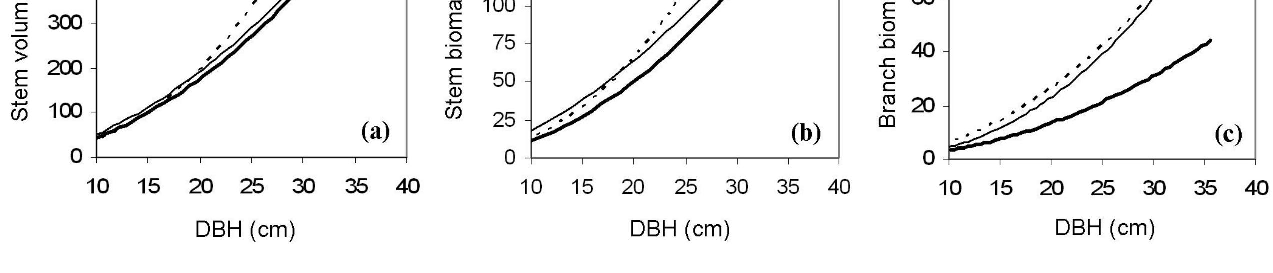


Table 3. Allometric relationships between diameter at breast height (cm), as predictor variable (*x*), and stem volume (dm^3), stem biomass (kg) and branch biomass (kg) as response variable (*Y*). For each model, goodness of fit, expressed by the Shapiro-Wilk statistic (*W*), is presented with its associated *p*-value. All models are significant at $p < 0.001$.

Clone	Trees harvested (n)	DBH range (cm)	Model	R^2	*F*-value	*W*	*P* < *W*
Stem volume							
DxN-3570	16	10.1–35.6	$Y = 0.3865x^2 + 1.7073x - 12.557$	0.98	412	0.93	0.25
MxB-915311	16	10.3–29.2	$Y = 0.148x^{2.3999}$	0.99	1198	0.97	0.75
DNxM-915508	16	9.8–33.8	$Y = 0.3564x^2 + 3.4442x - 18.79$	0.97	244	0.95	0.43
Stem biomass							
DxN-3570	16	10.1–35.6	$Y = 0.1283x^2 + 0.0109x - 1.3952$	0.98	367	0.97	0.86
MxB-915311	16	10.3–29.2	$Y = 0.0575x^{2.3464}$	0.97	528	0.94	0.30
DNxM-915508	16	9.8–33.8	$Y = 0.1033x^2 + 1.4503x - 6.7109$	0.96	187	0.97	0.73
Branch biomass							
DxN-3570	16	10.1–35.6	$Y = 0.0289x^{2.0531}$	0.94	200	0.99	0.99
MxB-915311	16	10.3–29.2	$Y = 0.0483x^{2.1026}$	0.93	177	0.95	0.47
DNxM-915508	16	9.8–33.8	$Y = 0.0196x^{2.3596}$	0.95	267	0.96	0.62

2.4. Statistical Analyses

ANOVA tables were constructed in accordance with Steel and Torrie [34], where degrees of freedom, sum of squares, mean squares and F values were computed. When a factor is declared statistically significant (Sites, Clones and Sites × Clones interactions), the standard error of the mean (SE) was used to evaluate differences between means for three levels of significance (*$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$). All of the ANOVAs were run with the complete set of data (four sites, three clones, four blocks = 48 experimental plots). For the presentation of results in figures, abbreviations of the names of plantation sites are used (Bromptonville = Bro, Magog = Mag, Roxton Falls = Rox and St-Isidore-de-Clifton = Sti).

A stepwise multiple regression procedure was used to determine which soil factors and which soil method explained the most variation in hybrid poplar volume yield [22,45,46]. Volume yield ($m^3ha^{-1}yr^{-1}$) was used as the response variable, while soils factors, measured by the different soil testing methods (nutrient stocks and nutrient concentrations in the 0–20 cm soil depth range, and nutrient supply rates measured in the A horizon), were used as predictor variables. Nutrient stocks in the 0–20 cm soil depth range were chosen over nutrient stocks at lower depths (20–40 and 40–60 cm), or nutrient stocks in the whole profile (0–60 cm) because they were best correlated with volume yield (Table 4).

Prior to regression analyses, a correlation matrix was used to eliminate soil variables showing high colinearity [47]. The correlation threshold for making a decision concerning variable elimination was set at $r > 0.5$. When two correlated predictor variables were identified, the one that was the most highly correlated with the response variable (volume yield) was chosen. For each stepwise regression, the choice of predictor variable entering the model (forward selection) was based on the change in F-statistic of the fitted model. All statistical analyses were done with JMP 6 from the SAS Institute (Cary, NC).

Table 4. Correlation coefficients (*r*) between hybrid poplar volume yield ($m^3ha^{-1}yr^{-1}$) and nutrient stocks measured at the different soil depths.

	Soil depths			
Nutrient stocks (kg ha^{-1})	**0–20 cm**	**20–40 cm**	**40–60 cm**	**0–60 cm**
P	0.67	0.54	0.48	0.66
Ca	0.38	0.001	0.24	0.24
K	0.67	0.65	0.61	0.66
Mg	−0.34	−0.33	−0.01	−0.25

3. Results and Discussion

3.1. Very High Wood and Biomass Production in Mature Hybrid Poplar Riparian Buffers Located on Small Farms of Southern Québec

Yield results from this study highlight the very high potential of riparian buffers to produce substantial wood volumes and biomass during a short time period, even if the study sites are located in extensive farmland (pasture, hayfield). Across the four riparian buffer sites, hybrid poplar productivity after nine years ranged from 116 to 450 m^3ha^{-1}, for stem wood volume (Figure 3a), and from 51 to 193 Mg ha^{-1}, for woody biomass (Figure 3b, Table 5). Consequently, the Site effect was by far the largest effect detected by the ANOVA followed by the Clone effect (Figure 3, Table 5), while the Site × Clone interaction for biomass and volume production was not statistically significant. As it was the case after six years of growth [1], the highest mean annual yields were obtained at the fertile site of Bromptonville after nine years, reaching 49.9 $m^3ha^{-1}yr^{-1}$ and 21.4 Mg ha^{-1}yr^{-1} (Table 5).

Very high mean annual yields were also observed at Roxton Falls (26.3 $m^3ha^{-1}yr^{-1}$ and 11.4 Mg ha^{-1}yr^{-1}) and at St-Isidore-de-Clifton (30.7 $m^3ha^{-1}yr^{-1}$ and 13.3 Mg ha^{-1}yr^{-1}) (Table 6). With yields above 25 $m^3ha^{-1}yr^{-1}$ on three of the four study sites, it is clear from this study that hybrid poplar riparian buffers are generally more productive than other hybrid poplar plantation systems established in the province of Québec [48]. Yields reported in the literature for Québec (excluding short rotation coppice) are generally between 15 and 25 $m^3ha^{-1}yr^{-1}$ for plantations established on high soil fertility sites in agricultural areas [22,49], while yields are generally below 5 $m^3ha^{-1}yr^{-1}$ for plantations established on clear-cut forest sites [48]. In fact, volume yields within the range measured in this study are generally observed in fast-growing plantations in tropical countries [50], which have much more favorable climates than southern Québec. For example, yield observed in eucalyptus and acacia operational plantations can reach 40 and 30 $m^3ha^{-1}yr^{-1}$, respectively [50]. There are several factors that can contribute to the high yield of hybrid poplar riparian agroforestry systems: (1) The high water availability in the riparian zone soils; (2) nutrients are continuously migrating from the adjacent agricultural land; (3) silt deposits that are periodically observed at the tree bases following flooding events, improve soil fertility, and (4) light availability is much higher than in large plantations because of the narrowness of the buffer strips.

Figure 3. Site and Clone effects for (**a**) total stem wood volume production (m^3ha^{-1}) and (**b**) total woody biomass ($Mg\ ha^{-1}$) production after nine years in hybrid poplar riparian buffer strips Total wood volumes and total woody biomass include trees of clone MxB-915311 that had broken at the end of the eighth and during the ninth growing seasons and that were harvested by the landowner. Vertical bars represent SE.

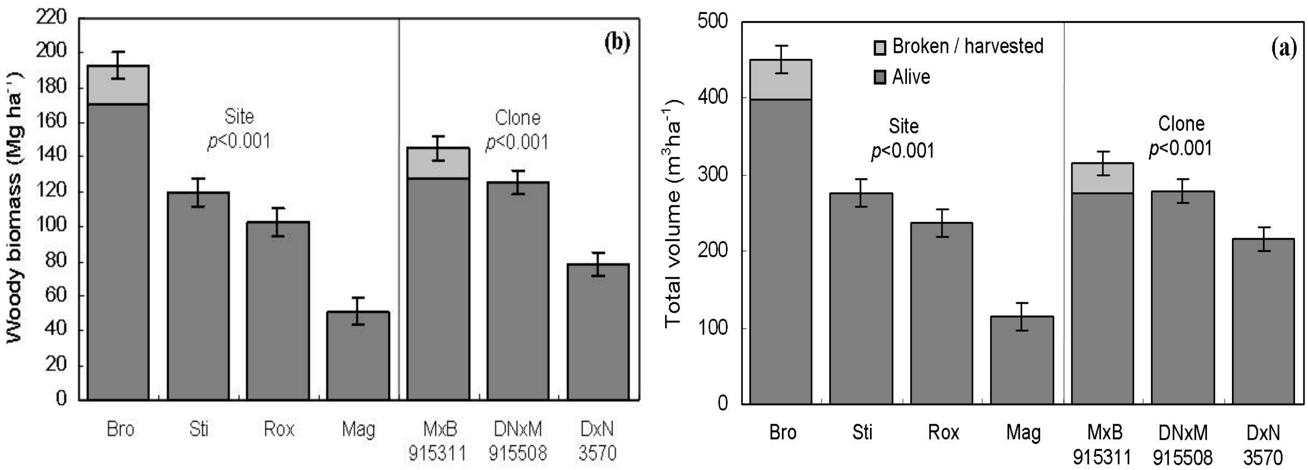


Table 5. Total aboveground dry biomass production ($Mg\ ha^{-1}$) at the four hybrid poplar riparian buffer sites and for the three poplar clones after nine years. Percent (%) of each tree compartment *versus* total woody biomass is indicated.

Sites and clones	Stem biomass[a] ($Mg\ ha^{-1}$)	%	Branch biomass[a] ($Mg\ ha^{-1}$)	%	Woody biomass[a] ($Mg\ ha^{-1}$)
Sites					
Bromptonville	142.1	74	50.7	26	192.8
St-Isidore-de-Clifton	88.4	74	31.3	26	119.7
Roxton Falls	76.1	74	26.7	26	102.8
Magog	37.7	74	13.5	26	51.2
SE	5.7		2.1		7.8
P<	0.001		0.001		0.001
Clones					
MxB-915311	103.8	71	41.7	29	145.5
DNxM-915508	92.6	74	33.1	26	125.7
DxN-3570	61.8	79	16.8	21	78.7
SE	5.0		1.8		6.8
p<	0.001		0.001		0.001

[a] Biomass calculations include trees of clone MxB-915311 that had broken at the end of the 8th and during the 9th growing seasons and that were harvested by the landowner.

Even the riparian buffer located on the poor, imperfectly drained, stony and unfertilized pasture site of Magog (Figure 1, Tables 1 and 2), which had earlier been considered marginal for wood production (only 4 $m^3ha^{-1}yr^{-1}$ after 6 years) [1], produced an interesting volume yield at the end of the ninth growing season (12.8 $m^3ha^{-1}yr^{-1}$) (Table 6). The Magog site now has a yield that falls within the desired mean annual increments for a short rotation woody crop (10–30 $m^3ha^{-1}yr^{-1}$) [51]. Therefore, even riparian zones of marginal or very extensive (unfertilized) agroecosystems might be interesting to generate relatively high wood volume in temperate regions. Further studies are needed to evaluate the yield potential of hybrid poplar buffer strips bordering intensively managed annual row crops (soy and maize) located in the St. Lawrence Valley Lowlands, where the best soils and mildest climate of the province of Québec are found. Yields are expected to be even higher in such systems.

Table 6. Mean annual volume yield ($m^3ha^{-1}yr^{-1}$) and mean annual woody dry biomass yield ($Mg\ ha^{-1}yr^{-1}$) increases from the sixth year to the ninth year at the four hybrid poplar riparian buffer sites (three clones mean) and for the three clones (four sites mean).

Sites and clones	Volume yield ($m^3ha^{-1}yr^{-1}$)		Increase ($m^3ha^{-1}yr^{-1}$)	Increase (%)	Biomass yield ($Mg\ ha^{-1}yr^{-1}$)		Increase ($Mg\ ha^{-1}yr^{-1}$)	Increase (%)
	6 years	9 years			6 years	9 years		
Sites								
Bromptonville	37.8	44.4–49.9[a]	6.6–12.1[a]	15–32[a]	16.1	18.9–21.4[a]	2.8–5.4[a]	15–33[a]
St-Isidore-de-Clifton	15.6	30.7	15.2	98	6.6	13.3	6.7	100
Roxton Falls	11.3	26.3	15.0	132	4.9	11.4	6.5	133
Magog	3.9	12.8	9.0	230	1.8	5.7	3.9	218
Clones								
MxB-915311	19.7	30.7–34.9[a]	11–15.2[a]	56–77[a]	9.2	14.3–16.2[a]	5.1–7.0[a]	55–76[a]
DNxM-915508	17.4	30.9	13.5	78	7.5	14.0	6.4	85
DxN-3570	14.3	24.0	9.7	68	5.3	8.7	3.4	65

[a] This yield variation is related to the inclusion or exclusion of trees of clone MxB-915311 that had broken at the end of the 8th and during the 9th growing seasons and that were harvested by the landowner.

The very high yield increases that occurred from the sixth to the ninth year (Table 6), suggest that after six growing seasons, none of the four riparian buffers had reached their maximal productivity in terms of mean annual increment. Even the buffer strip at Bromptonville, which already had a mean annual volume yield of 37.8 $m^3ha^{-1}yr^{-1}$ after six years (three clones mean), increased its yield by 12.1 $m^3ha^{-1}yr^{-1}$ to reach 49.9 $m^3ha^{-1}yr^{-1}$ after nine growing seasons (Table 6). However, the mean annual volume yield increase during this 3-year period was much lower (6.6 $m^3ha^{-1}yr^{-1}$) when yield calculations were done only with live standing trees (Table 5). The largest yield increases were observed at the intermediate sites of St-Isidore-de-Clifton and Roxton Falls, where mean annual volume yield increased by an average of 15 $m^3ha^{-1}yr^{-1}$ from year six to year nine (Table 6).

Finally, despite the very high relative yield increase at the Magog site (230%), the productivity gap, in terms of mean annual yield, between this less fertile site (Figure 1, Tables 1 and 2) and the three other sites, has widened (Table 6). This highlights the important economic advantage, in terms of productivity gain, that can be made simply by growing hybrid poplars in the most fertile riparian zones. From the landowner's economic perspective, selecting high quality sites is the main factor to consider. As shown for intensive white spruce plantations in Québec, the first factor affecting plantation profitability for the private landowner is site quality, followed by the use of improved genotypes and silvicultural treatments, respectively [24]. Site quality, in terms of soil fertility and climate, was by far the most important factor affecting hybrid poplar yields in southern Québec upland farm sites [22].

3.2. Some Clones Reached Their Biomass Production Limit after 9 Years

A significant Clone effect ($p < 0.001$) was detected for volume and woody biomass production after nine years, with total volume and woody biomass production ranging from 216 to 314 m^3ha^{-1} and from 78.3 to 146 Mg ha^{-1} (Figure 3, Table 5). Clone ranking in terms of yield remains similar from year six to nine, with clone MxB-915311 being the most productive, and clone DxN-3570 being the least productive (Table 5). Yet, if broken / harvested trees are not included in calculations, the production of clones MxB-915311 and DNxM-915508 were not significantly different after nine years (Figure 3, Table 6). We suggested earlier that clone MxB-915311 might not be suitable for the production of solid wood products over long rotation in riparian buffers [1]. The allometric relationships presented in this study, along with field observations, provide additional evidence supporting this recommendation.

Between 5 to 20 cm DBH, allometric relationships between DBH and stem volume or stem biomass are similar for the three clones (Figure 2a, b). However, for larger trees (DBH > 20 cm), clone MxB-915311 accumulated much more stem volume and biomass for a given DBH than the two other clones. This may be related to its forking habit, which generates multiple main stems (Figure 4). Furthermore, at equivalent DBH, clone MxB-915311 and clone DNxM-915508 had much more branch biomass than clone DxN-3570 (Figure 2c). This particular tree architecture of clone MxB-915311 is consistent with its inherent fragility when planted in windy environments, such as riparian buffer strips. Several trees of this clone had broken at the end of the eighth and during the ninth growing seasons (Figure 4). These broken trees accounted for 150 m^3 of wood at the Bromptonville site. Clearly, this clone had reached its physical limit to produce biomass after 9 years on the best site.

Thus, in riparian buffers designed for production, clone MxB-915311 should only be planted to produce biomass or pulp wood on short rotations, given its high productivity at a young age [1] and its high susceptibility to mechanical breakage when it reaches larger diameters (DBH > 20 cm). These observations are consistent with the fact that *P. deltoides* and DxN hybrids are now favored over balsam poplar hybrids for long term uses such as shelterbelt plantings in the northern North American Prairies [52].

Given the high volume of broken woody biomass that has been produced by clone MxB-915311 at Bromptonville after only nine years, it is clear that this clone may be used to provide large amounts of coarse woody debris in riparian zones within a short time frame. These coarse woody debris are key structural attributes for both aquatic and terrestrial biodiversity [53,54], but they also have important water quality functions, as reviewed by Dosskey *et al.* [10]. Since growth of natural mature riparian forest and production of coarse woody debris often takes decades, even centuries following forest removal [55], hybrid poplar planting with clones such as MxB-915311 may be used to rapidly restore these key structural attributes. Conversely, the use of clones that are susceptible to mechanical breakages in buffer design may result in important gaps in the canopy over the years, which will increase the quantity of light reaching the understory. This situation may negatively affect native plant communities given the strong positive relationship between canopy openness and richness or abundance of exotic plants in poplar buffer understories [15].

With its low branch biomass and straight bole, clone DxN-3570 might be a good candidate for riparian agroforestry systems that are designed for the production of solid wood products on longer rotations (Figures 2c and 4). Although clone DxN-3570 was the least productive across the four study sites, very high yields were obtained at the fertile Bromptonville site after 9 years (44.3 $m^3ha^{-1}yr^{-1}$). In addition, *Populus deltoides* × *P. nigra* (DxN) hybrids generally have higher wood density and better mechanical proprieties than hybrids related to the *Tacamahaca* (balsam poplars) section [29,56]. Clone DNxM-915508 also produced a straight bole. However, its high branch biomass (Figure 2c) might increase labor costs or time associated with pruning operations, a silvicultural treatment often recommended for the production of knot free wood [28].

Figure 4. On the left, straight bole of clone DxN-3570 planted in riparian buffer strips. On the right, mechanical damage to clone MxB-915311 at the Bromptonville site following strong winds at the end of the eighth growing season.

3.3. Which Soil Testing Method can be Used to Assess Riparian Soil Fertility for Hybrid Poplar Agroforestry?

Results from the stepwise regression suggest that the three soil testing methods used in this study (nutrient supply rates measured with ion exchange membranes, nutrient stocks in the 0–20 cm soil depth range, and nutrient concentrations in the 0–20 cm soil depth range) gave similar models for predicting hybrid poplar volume yield across the four study sites (Table 7). Independently of the soil testing method used, available soil P, in terms of P supply rate, available P stock or available P concentration, was always the first soil factor explaining hybrid poplar volume yield in this study (Table 7). This trend was also observed for NxM, MxB and DNxM hybrids across a gradient of climate and soil fertility in abandoned farmland of southern Québec [22].

The three soil testing methods used in this study may be useful to understand relationships between poplar productivity and riparian soil fertility since soil fertility variables measured with the different methods are highly correlated (Table 8). Strong correlations were observed for a given nutrient when nutrient supply rates were plotted against nutrient stocks (r = 0.68–0.83, $p < 0.001$) or nutrient concentrations (r = 0.57–0.67, $p < 0.001$) (Table 8). Strong correlations between NO_3 supply rate measured with PRS-Probes, soil NO_3 concentration, or nitrification, have also been observed in hybrid poplar buffers [57]. Still, the best correlations were generally observed when nutrient supply rates were plotted against nutrient stocks. This indicates that nutrient supply rate measured with ion exchange membrane (PRS-probes) may better reflect soil nutrient stocks, which are a function of bulk density, stoniness and nutrient concentrations, than nutrient concentrations alone (Table 8). The weaker model in the stepwise regression, in terms of determination coefficient (R^2), was also the one developed with nutrient concentrations as predictor variables (Table 7). It has also been shown in agricultural studies that nutrient supply rates measured over a wide range of soil types with ion exchange membranes were a better index of nutrient availability than the use of nutrient concentrations obtained from chemical extractions [31].

Table 7. Results of stepwise regressions between nutrient supply rates, nutrient stocks or nutrient concentrations in the 0–20 cm soil depth range (predictor variables), and hybrid poplar volume yield ($m^3ha^{-1}yr^{-1}$) (response variable) measured at the end of the ninth growing season (n = 48). Volume yield calculations include trees of clone MxB-915311 that had broken at the end of the eighth and during the ninth growing seasons and that were harvested by the landowner. All models and predictor variables are significant at $p < 0.05$.

Nutrient supply rates ($\mu g\ 10cm^{-2}\ 20d^{-1}$)	**Parameter estimate**	R^2	**Nutrient stocks ($kg\ ha^{-1}$)**	**Parameter estimate**	R^2	**Nutrient concentrations ($mg\ kg^{-1}$)**	**Parameter estimate**	R^2
P	2.53	0.41	P (available)	0.098	0.45	P (available)	0.25	0.36
K	0.03	0.67	K	0.042	0.65	Mg	−0.042	0.51
Mg	−0.023	0.75	Ca	0.0049	0.73	K	0.079	0.67
Intercept	21.8		Mg	−0.023	0.79	*Intercept*	21.4	
			Intercept	12.4				

Table 8. Correlation coefficient (*r*) obtained from pairwise correlations between nutrient stocks ($kg\ ha^{-1}$) or nutrient concentrations ($mg\ kg^{-1}$) in the 0–20 cm soil depth range and nutrient supply rates in the 0–10 cm soil horizon measured with PRS-probes. All correlations are significant at $p < 0.001$.

Nutrient stocks ($kg\ ha^{-1}$) vs nutrient supply rates ($\mu g\ 10cm^{-2}\ 20d^{-1}$)	***r***	**Nutrient concentrations ($mg\ kg^{-1}$) vs nutrient supply rate ($\mu g\ 10cm^{-2}\ 20d^{-1}$)**	***r***
Available P stock vs P supply rate	0.78	Available P concentration vs P supply rate	0.72
Ca stock vs Ca supply rate	0.77	Ca concentration vs Ca supply rate	0.57
K stock vs K supply rate	0.83	K concentration vs K supply rate	0.73
Mg stock vs Mg supply rate	0.68	Mg concentration vs Mg supply rate	0.67

Beyond result accuracy, numerous advantages and disadvantages are associated with the use of the different soil testing methods. From a practical point of view, it is clear that the more convenient soil testing method is to assess only soil nutrient concentrations. With this method soil samples are easily collected in the field without specific equipment and, once dry, soil samples can be sent directly to a soil analysis laboratory. Therefore, a landowner could easily collect soil samples by himself from different areas of his fields, and soil analysis results could be used to identify the more fertile areas. The same approach could be used at a regional scale to identify high quality riparian sites for hybrid poplar agroforestry. Although very convenient, the sole use of nutrient concentrations as indicators of soil fertility also has its disadvantages. Depending on the chemical extraction solution used to process soil samples, nutrient concentration measurements for a particular nutrient will vary greatly [58], which makes standardization very difficult among results obtained from different extraction methods. In addition, accurate evaluation of soil NO_3 is complicated by the fact that the NO_3 concentration in a soil sample can change significantly if the sample is not handled properly once collected [37]. Therefore, soil samples should be dried immediately after sampling, a procedure that is not always logistically possible [37].

The use of PRS-probes ion exchange membranes in long term burials (20 days in this study) has the advantage of providing information, in undisturbed conditions, on the dynamics of nutrient supply, which are affected by processes such as mineralization and dissolution, but also by factors such as soil temperature and moisture content [31]. PRS-probes are easy to install in most soil types, although probe breakage may occur in stony soils, as was the case at the Magog site (Figure 1a). Furthermore, we have seen, on rare occasions, wildlife disturbance and trampling of the probes. A source of distilled or deionised water is also required to wash the probes when they are removed from the soil. One of the challenges with the use the PRS-probe technology, is that multiple site assessments (with long time burials) requires that ion exchange membranes be buried simultaneously and for the same time period. This can be troublesome if there are several distant sites to assess.

From a practical perspective, the PRS-probes can be a useful tool to rank potential sites for hybrid poplar riparian agroforestry within a region given the strong relationship between poplar yield and nutrient supply rates [1] (Table 7). However, a standardized approach needs be developed for hybrid poplar site assessment because soil nutrient status in riparian buffer strips may evolve with time and with ongoing upland agricultural activities. While NO_3 supply rate best predicts hybrid poplar growth in the same riparian buffer strips after 6 years [1], P supply rate was the best predictor variable for volume yield after the 9th growing season (Table 7). This discrepancy might be related to the change in NO_3 and P supply rates measured at Bromptonville and St-Isidore-de-Clifton. While NO_3 and P supply rates were similar after 6 years at these two sites [1], a significantly higher NO_3 supply rate was measured at St-Isidore during the ninth year, while P supply rate was significantly higher at Bromptonville (Table 2). The higher NO_3 supply rate measured during the ninth growing season at St-Isidore-de-Clifton may be related to the application of inorganic N fertilizer in the adjacent pasture (N application rate = 18 kgha−1 per 5 years), one month prior to the installation of PRS-probes in the soil (Table 1).

For the moment, Western Ag provides a service to crop producers in western Canada and North Dakota only. The service is delivered through field service representatives, who obtain soil samples that are incubated with PRS-probes for 24 hours under standardized conditions and, more importantly, used with a computer model (PRS-probe Nutrient Forecaster) to assist with the planning of which crops to grow and how to fertilize them (Eric Bremer, pers. com., Western Ag). A similar tool could be developed regionally for hybrid poplar plantation site selection.

Concerning the use of nutrient stocks, we have identified many drawbacks with this approach for practical application to soil testing in riparian agricultural zones. First, the determination of nutrient stocks, as it is also the case for determining carbon stocks, requires that soil bulk density be assessed adequately. The core method has become ecologists' favored method for bulk density measurements [39]. However, since bulk density estimation with the core method can be done using three different methods, which reflect how coarse fragments (>2 mm) are handled in calculations, inconsistencies in nutrient or carbon stock calculations may occur [39]. To increase the precision of bulk density measurements, Throop *et al.* [39] suggest removing coarse fragments from cores by sieving, and then calculate bulk density as the soil dry mass divided by the core volume. Consequently, this approach is more time-intensive than the common determination of core bulk density obtained from the dry mass of the entire core divided by core volume [39]. Furthermore, despite the widespread use of the core method to quantify bulk density, it is clear that under many circumstances it is inappropriate. For example, the core method will underestimate nutrient stocks when coarse fragments are larger than the size of the corer [59]. Consequently, in soils with a high volume of coarse fragments, a very large volume of soil needs to be excavated to properly measure the soil volume occupied by stones [60], a procedure that is very time consuming, labor intensive and costly.

In short, for practical reasons, we would recommend the use of both soil nutrient concentrations obtained from chemical extractions and soil nutrient supply rates obtained from ion exchange membranes (PRS-probes) to assess soil fertility in hybrid poplar riparian agroforestry systems.

It is also important to mention that nutrients stocks, concentrations and supply rates reported in this study were only measured once in the ninth growing season. Therefore, relationships between nutrient availability and hybrid poplar productivity should be interpreted with caution given the uncertainties associated with the snapshot approach used to measure nutrient availability. Nutrient availability in a riparian buffer may fluctuate between growing seasons and during a single growing season as it is influenced by management practices in the adjacent agricultural land use, local climate (precipitation and temperature), natural disturbances such as flooding, water table level fluctuations and biological processes such as nutrient uptake by trees, organic matter mineralization, denitrification and bacterial immobilization [61–65]. Repeated measures of nutrient availability within and between growing seasons should be done in further studies to have a more complete picture of the causal relationship between site fertility and poplar growth in agricultural riparian zones. Nevertheless, one-time soil nutrient measurements have been shown to be strong predictors of hybrid poplar yields over eight years of growth [22], and are therefore very useful for the selection of new plantation sites, without the need for multiple soil nutrient measurements over an entire season and over several years.

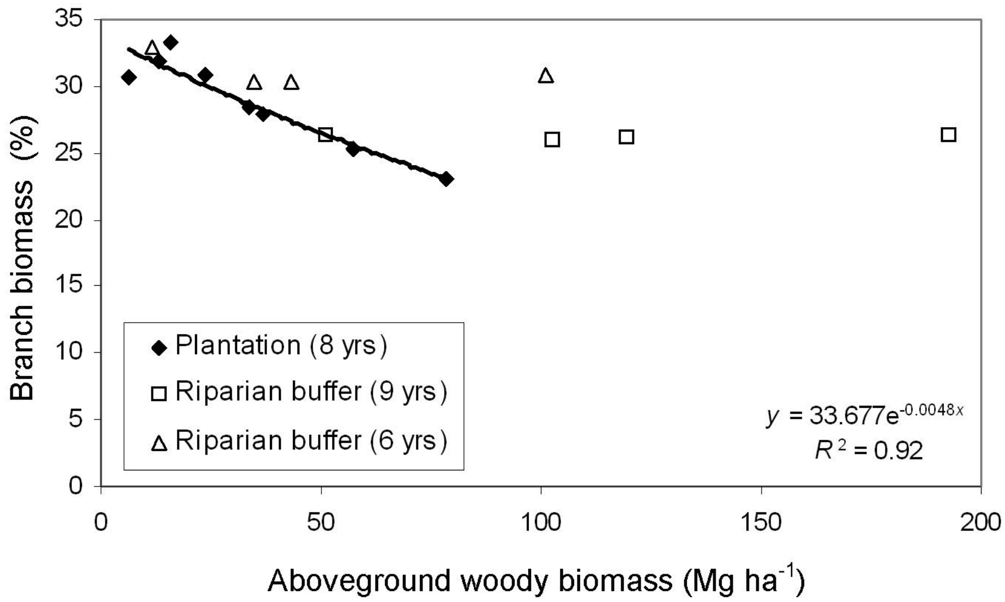
3.4. Agricultural Riparian Zones as Prime Areas for Sustainable Poplar Production: Some Considerations for Landowners

With volume and woody biomass yields ranging from 26.3 to 49.9 $m^3ha^{-1}yr^{-1}$ and from 11.4 to 21.4 Mg $ha^{-1}yr^{-1}$ after nine years, obtained at the three most productive sites (Table 6), it is clear that hybrid poplar riparian buffers can produce very high quantities of wood and biomass, when compared to other poplar plantation systems in Québec [48], while increasing nutrient accumulation, carbon sequestration and habitat quality for native plants [14,15]. It is also important to mention that the hybrid poplar riparian buffer strips studied had received very minimal silvicultural treatments; there was no site/soil preparation and there was a single local (1 m^2/tree) herbicide application early during the first growing season. It has been argued that improving the sustainability performance of bioenergy systems can be achieved by minimizing emissions to air, water and soil, and by developing systems that maintain or improve biodiversity [66]. With that in mind, hybrid poplar riparian buffers can contribute to improve the sustainability of biomass and timber production in temperate regions.

Some considerations concerning tree harvesting in riparian zones could also improve the sustainability of biomass production in agricultural riparian zones. To maintain benefits for biodiversity, wood or biomass harvest in riparian buffers should be planned at both farm and landscape levels, in order to continuously maintain a proportion of unharvested patches, which can be achieved by rotational and/or selective harvests [67–69]. Rotational or selective harvests will also be important to maintain other functions, such as the nutrient accumulation potential of the buffer [70]. Rotational harvest could also reduce impacts on soil erosion [71]. Heavy machinery, which is often used to harvest biomass or timber, can cause soil compaction; a problem that can be overcome if harvest only occurs when the ground is frozen [72].

This study also provides evidence that trees growing in agroforestry systems such as riparian buffers may have different biomass allocation patterns compared to trees growing in forests or in plantations (Figure 5). A significant decline in the proportion of branch biomass is generally observed with increasing tree size for both conifer and hardwood species growing in natural forests [73]. This trend has also been observed along a productivity gradient in eight year-old hybrid poplar plantations of southern Québec [22] (Figure 5). However, in this study the proportion of branch biomass of nine year-old poplars remains the same across the four sites (26%), although aboveground woody biomass accumulation varies considerably (Table 5) (Figure 5). The same trend was observed when the riparian buffers were six years old (Figure 5). This suggests that hybrid poplars grown in high light environments, such as riparian buffer strips, will produce more branch biomass than hybrid poplars grown in large conventional plantations. Consequently, landowners who wish to produce veneer lumber in buffer strips may have to dedicate more resources to pruning operations than in conventional plantation systems.

Figure 5. Significant relationship ($p < 0.001$) between mean aboveground woody biomass measured at each site and branch biomass expressed as a percentage of aboveground woody biomass in eight year-old hybrid poplar plantations of southern Québec (data obtained from Truax *et al.* [22]). No significant relationship links the two variables at the four hybrid poplar buffer sites (at six or nine years).



Another important consideration is related to the marketing of timber and biomass produced in riparian zones. As observed in the US cornbelt region, markets for biomass are presently lacking and market-pull will be required to organize harvesting, processing, storage and transport of woody biomass [74]. Foresters interviewed in the same region noted that one of the biggest constraints to woody biomass production on privately owned agricultural land would be the size of individual plots, but also the weak return on investments [74]. The same constraints may be associated with the production of woody biomass and timber in farmland riparian zones of southern Québec. In a recent provincial report, it was stated that local markets for biomass for bioenergy are lacking in agricultural areas of Québec, that provincial regulations are overly restrictive and that economic benefits are uncertain [75]. Another important logistical constraint lies in the linear configuration of riparian corridors, which results in a dispersed resource at the landscape level. Therefore, longer average hauling distances to lumber and/or biomass facilities characterize linear plantation systems when compared to large-scale plantations, which can be concentrated near the facility. This is an important issue since break-even costs of biomass production in riparian agroforestry systems is largely dependent on transportation distance to transformation centers [76].

In that context, the best alternative might be to use hybrid poplar biomass directly on the farm, as firewood (or chips) for heating farm buildings and houses, as it was the case at the Bromptonville site (Figure 6). This would in turn help reduce harvesting pressures for firewood in the last few remaining natural forests in the agricultural landscape. Establishing wide riparian buffers (10–15 m) might also be a way to reduce hauling distance to biomass facilities, while increasing the quality of other ecosystem services (non-point source pollution control, habitat for biodiversity, soil stabilization, flood control, *etc.*) [77].

Figure 6. Wood harvested in hybrid poplar riparian buffer strips can be used as firewood for farm buildings and houses, as it was the case following a partial harvest (one in nine trees) in 2008 (sixth growing season) at the Bromptonville site.

To increase the economic feasibility of hybrid poplar buffer implementation on farmland, ecosystems services, such as water quality and habitat protection, erosion and flood control, carbon sequestration, *etc.*, should no longer be considered as externalities [78]. An appropriate valuation of these ecosystem services [79] is needed, because this added value might be the only way to offset the economic loss associated with the conversion of some areas of agricultural systems into riparian agroforestry systems, especially in the current context of high annual crop value [20].

4. Conclusion

Yield results from this study highlight the very high potential of riparian buffers to produce wood and biomass over a short time period, even in extensive farmlands. After nine years, yields reaching 49.9 $m^3ha^{-1}yr^{-1}$ and 21.4 Mg $ha^{-1}yr^{-1}$ were observed on the most fertile site. From year six to nine, relatively high yield increases (8.9–15.1 $m^3ha^{-1}yr^{-1}$) were observed at all sites, but the productivity gap, between the less fertile site and the three other sites, had widened. Clone MxB-915311 was the most productive across the four sites. However, at the most productive site this clone experienced severe breakages on many trees, suggesting that it had reached its biological limit to produce wood or biomass after only nine years. This trend might be related to the particular architecture of this clone (forking habit and high branch biomass).

Independent of the soil testing method used, available soil P, in terms P supply rate, available P stock or, available P concentration, was always the first soil factor explaining hybrid poplar volume yield. Because soil fertility variables measured with the different methods are highly correlated, the three soil testing methods used in this study may be useful to understand relationships between poplar productivity and riparian soil fertility.

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Conflict of Interest

The authors declare they have no conflicts of interest.

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