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Thinning and Gap Harvest Effects on Soil, Tree and Stand Characteristics in Hybrid Poplar Bioenergy Buffers on Farmland

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Abstract: Linear bioenergy buffers planted with fast-growing trees along field edges are increasingly used to address challenges related to sustainable biomass production, climate change mitigation (i.e., carbon storage and microclimate regulation), water quality protection, and forest habitat connectivity in agricultural landscapes. This study assessed: (1) the extent to which 15 m wide hybrid poplar bioenergy buffers (1666 stems/ha) with closed canopy responded to thinning (diamond pattern of tree removal); (2) the regrowth of poplars from cut stumps following gap harvesting; (3) the effects of harvesting treatments on soil microclimate and nutrient availability; and (4) the spatiotemporal pattern of tree growth in unthinned plots. After three post-thinning years, results showed a strong growth response of seven-year-old hybrid poplar trees to thinning (12% increase in diameter and 30% increase in individual stem volume), accompanied by a slight decline in stand productivity. Gap harvesting was not an effective treatment to regenerate the stand from shoots growing from cut stumps because of the high deer browsing. Overall, thinning had marginal effects on soil nutrients and microclimate, compared with gap harvesting, which increased soil temperature, soil moisture, and the availability of several macro and micronutrients. However, harvest effects on soil nutrients were mostly observed during the first postharvest year, with the exception of soil nitrate, which was lowest in the gap treatment during the second postharvest year. Finally, the spatial pattern observed in tree growth between the buffer rows suggests that other more operational thinning patterns (row or corridor thinning) need to be evaluated in linear buffers.

Keywords: *Populus*; agroforestry; biomass; stand productivity; nutrient availability; soil nitrate; soil moisture; soil temperature; stump sprouting; deer browsing

1. Introduction

In the agroecosystems worldwide, bioenergy buffers planted with fast-growing tree species are being increasingly established because of the multiple ecosystem services they provide (e.g., carbon (C) storage, excess nitrogen (N) and phosphorus (P) removal from soils, microclimate improvement, biomass production, habitat creation, and soil stabilization) on a decanal time frame [1–6]. These multifunctional buffers could be implemented to rapidly address challenges related to sustainable biomass production, climate change mitigation and adaptation (i.e., carbon storage and microclimate regulation), water quality protection, and forest habitat connectivity in agricultural landscapes. Producing fuelwood in bioenergy buffers rather than in farm woodlots could also create opportunities to protect forested areas and improve their C storage capacity [7,8]. The success of such buffers for providing multiple ecosystem services over the years will, however, depend on their design, species composition, location within the landscape, management in terms of biomass harvesting strategies, and regrowth potential [4,8–10].

The effects of harvesting on soil characteristics and biomass production in agricultural buffers have been primarily evaluated in *Salix* spp. coppices, in *Platanus hybrida* Brot.

coppices or in herbaceous systems [1,11,12]. No studies have evaluated harvest effects in more widely spaced hybrid poplar (*Populus* × spp.) buffers planted to produce firewood, a common energy source for heating in rural areas of the northern temperate zone [13,14]. Only the economic potential of different management scenarios has been evaluated for such tree buffers [15]. Therefore, studies on harvesting treatment effects on soil, stem quality, and stand productivity are necessary as they will contribute to quantify how bioenergy buffer management will affect the provision of various ecosystem services on farmland (i.e., carbon storage, nonpoint source pollution control, bioenergy and timber production, and microclimate regulation).

Partial harvesting treatments such as thinning and gap harvesting may be particularly suited for biomass production in agricultural buffers because a forested structure that supports important functions in agroecosystems (i.e., microclimate, forested habitats and corridors, land aesthetics) is maintained following tree harvest. Compared with clearcutting, these partial harvesting treatments may also have lower impacts in terms of soil C loss, nutrient leaching, and microclimate modification [16–18] while being more socially acceptable [19]. These elements need to be considered, especially where agricultural buffers border sensitive areas (i.e., streams, wetlands, or small forest patches). Compared with clearcutting, partial harvesting treatments are also more likely to provide continuous supplies of biomass through time in order to meet the annual needs for firewood on the farm while maintaining C stocks in the stand [7]. However, partial harvesting treatments are often not economically justified in hybrid poplar plantations [20–23], so treatments such as thinning have been little studied in controlled experiments.

In planted stands, thinning (i.e., the selective removal of trees) is generally used to improve the growth rate of the remaining trees by reducing the level of intraspecific competition for resources [24]. In that perspective, many landowners of pulpwood or energy plantations have thinned their hybrid poplar stands to allow sawlog production on extended rotations [21–23]. Thinning can also affect stand productivity, positively or negatively, depending on tree species, planting density, rotation length, thinning regime (i.e., timing, frequency and intensity), site conditions, and stand structure [25–30]. In hybrid aspen (*Populus tremula* L. × *Populus tremuloides* Michx.) stands planted at approximately 1600 stems/ha, low to moderate thinning treatments slightly reduced productivity but greatly increased stem diameter growth after five post-thinning years [31]. Conversely, a high-density hybrid poplar plantation thinned after four years (half of the 5000 stems/ha removed) experienced no productivity loss at six years [32]. In planted poplars, thinning intensity generally affects the magnitude of the growth response at the tree-level and stand-level, with the most significant productivity losses and diameter gains observed in the more heavily thinned stands [31,33]. Some poplar species may also respond poorly to thinning depending on when the treatment is undertaken during stand development. Cottonwood (*Populus deltoides* Bartr. ex Marsh.) is known to respond poorly to release following crowding, and early thinning is recommended for this species, even in widely spaced (700–800 stems/ha) plantations [34,35].

Gap harvesting is generally undertaken in hardwood forests to emulate canopy gaps created by natural agents (insects, diseases, ice storms, fire) [36]. The gap size prescribed is generally based on the shade tolerance of the species to be regenerated, with large gaps used for shade-intolerant species such as poplars [36]. Currently, we are not aware of studies investigating to which extent hybrid poplar can be regenerated from cut stumps following a gap harvest. An important factor that can compromise this regrowth process is the overabundance of Cervidae species. In northeastern North America, the white-tailed deer (*Odocoileus virginianus* Zimm.) is known to severely browse newly established hybrid poplar plantations and agroforestry systems [37,38]. For this reason, large planting stocks and intensive vegetation control are used to allow planted poplars to grow in height above the browse line during the first growing season [37,38]. However, poplar stands regenerating from cut stumps may be highly vulnerable to browsing damage as shoots growing at ground level are easily consumed by deer.

By modifying stand structure, harvesting treatments can affect microclimate, competitive interactions between trees, nutrient inputs to soil from litterfall, and ultimately element cycling within the stand [18,39–41]. A recent meta-analysis has concluded that thinning promotes soil N and P cycling and increases soil fertility [41], but a decline in soil fertility has also been observed in thinned stands [42]. In widely spaced poplar plantations (500 stems/ha), increases in soil water content, water table height, soil temperature, organic mineralization, and N availability have been observed following thinning, especially in the more intensive treatments [40]. Similarly, in a 10,000 stems/ha *Populus trichocarpa* Torr. & A.Gray ex. Hook. plantation, an increase in soil temperature was only observed in the 80% thinning treatment but not in the 50% thinning treatment [43]. In coniferous forests, the selective removal of individual trees was not associated with elevated soil nitrate (NO_3), while all gap harvesting treatments (gap size ranging 0.1–10 ha) were, which suggests that harvesting single trees would reduce NO_3 losses vs. creating gaps [17]. Thus, more intensive harvesting treatments are expected to have the greatest effects on soil microclimate and nutrient availability.

A particular spatial pattern of tree growth is also expected in linear buffers because trees in hedgerows have high access to soil resources and light, especially in the row adjacent to the edge of the cultivated field. Previous studies in willow bioenergy buffers have shown that nutrient inputs from adjacent agricultural activities affected biomass production patterns along the buffer transect, with the first rows bordering cultivated fields being the most productive and the ones that contributed the most to nutrient removal via uptake and harvesting [5,12]. Evaluating such spatial patterns of tree growth over time can indicate when and where tree harvesting should be conducted in multiple row buffers.

The objectives of this study were to evaluate: (1) to which extent hybrid poplar bioenergy buffers respond to thinning at the tree and stand scales; (2) the regrowth of poplars from cut stumps following gap harvesting; (3) the effects of thinning and gap harvesting on soil microclimate and nutrient availability; and (4) the spatiotemporal pattern of tree growth in unharvested control plots. We hypothesized that hybrid poplars would have a strong positive growth response at the tree level following thinning, given that hybrid poplars strongly respond to increases in soil nutrient and light availability [38,44,45]. We also hypothesized that the more intensive harvesting treatment (i.e., gap harvesting) would have the most significant effects on soil microclimate and nutrient availability [17,40]. Finally, we hypothesized that the greatest tree growth would occur in the edge rows of the buffers, especially in the tree rows facing the cultivated fields.

2. Materials and Methods

2.1. Study Site

This study was conducted in the municipality of St-Benoît-du-Lac, on a 216 ha property owned by a Benedictine monastic community, located in the Estrie region of southern Québec, Eastern Canada (45°10′ N; 72°16′ W). In 2011, 15 m wide linear bioenergy buffers containing five tree rows were planted downslope of hayfields. A detailed map of the study area and site can be found in a previous study [46]. The management objectives of the studied multifunctional buffers were to reduce nonpoint source pollution from adjacent cultivated fields, increase carbon storage on farmland, and produce firewood for heating the Abbey buildings [37,47].

The soils at the study site are Dystric Brunisols developed from thick till deposits derived from slate [48]. They are classified as Magog loam or Ascot sandy loam, with a relatively high stone content in the surficial horizon and a good to imperfect drainage [48]. Physicochemical characteristics of the soil underneath the poplar buffers were the following: texture, varying from loam to silty loam; pH_{water}, 6.3; available P, 98 kg/ha; Ca, 4903 kg/ha; K, 226 kg/ha; Mg, 502 kg/ha; cation exchange capacity, 20 meq/100 g; C/N ratio, 9.6; organic matter content, 8.4%; base saturation, 64.7% [46]. The study area is characterized by a continental moderate subhumid climate, with a growing season of 180 to 190 days [49]. Thirty-year climate normal data from the nearest meteorological station of Magog indicate a

mean annual temperature of 5.6 °C and total annual precipitation of 1142 mm [50]. Growing season (May to September) temperatures and precipitations are presented on a monthly basis for the three postharvest years covered in this study (2018–2020) (see Figure 1).

Plowing and disking were performed in fall 2010 to prepare the site prior to planting. In May 2011, bare-root stocks (±180 cm of height) were planted to a depth of 30 cm using a shovel. The genotype planted was DN×M-915508, a hybrid resulting from the cross between *P. deltoides* × *Populus nigra* L. and *Populus maximowiczii* Henry. This genotype is known to be highly productive across a variety of sites in the study area, and it shows good disease resistance/tolerance in genetic trials [51–53]. Competing vegetation control was carried out in June of the first two growing seasons, with a spot herbicide application of glyphosate (≈1 m^2/tree).
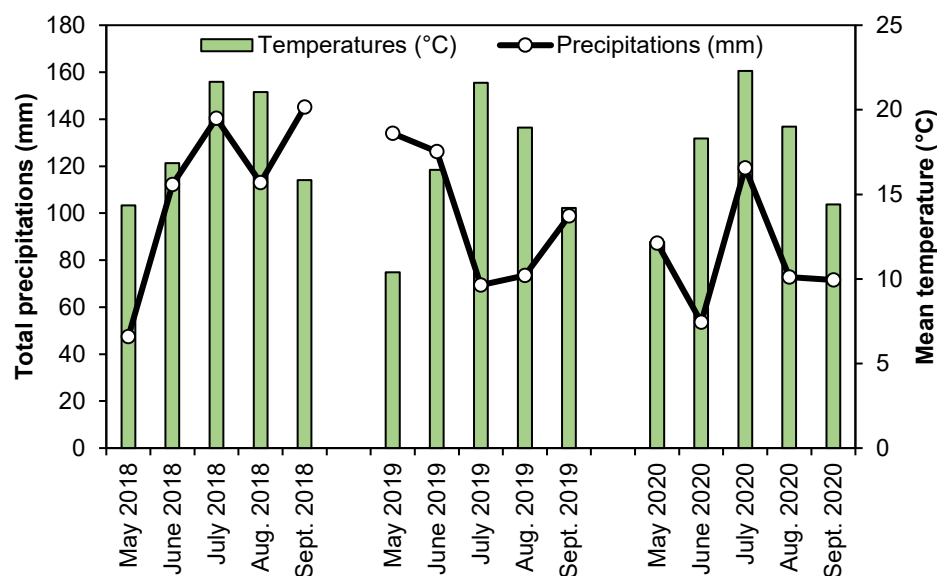

Figure 1. Monthly total precipitations and mean temperature during the three growing seasons of the study. Data from the nearest meteorological station of Magog (QC, Canada) were used [54].

2.2. Experimental Design

The experimental design had five blocks (i.e., repetitions), well distributed at the margin of the different hayfields of the farmland. Each block contained three harvesting treatments (gap harvesting, thinning, unharvested control) for a total of 15 experimental plots (5 blocks × 3 harvesting treatments). Each plot initially contained 15 trees and measured 15 m wide by 6 m long (90 m^2), with 5 tree rows and 3 trees per row, planted with a spacing of 2 m on the row and 3 m between rows (i.e., a planting density of 1666 stems/ha). Such a planting density had been recommended for fuelwood production in other cold temperate locations [55].

At the end of the seventh growing season, in mid-fall of 2017, 110 trees were harvested (whole-tree harvest with branches removed from the site) to create the gap harvesting and thinning treatment plots. Trees were felled manually with a chainsaw, and all the woody biomass was transported by hand out of the plots. In the thinned plots, 7 trees out of 15 were harvested to create a diamond pattern, while all 15 trees in the gap harvesting treatment plots were harvested (Figure 2). A one-way analysis of variance (ANOVA) showed no significant harvesting treatment effect on the mean diameter at breast height (DBH) ($p = 0.62$) across plots prior to tree harvesting.
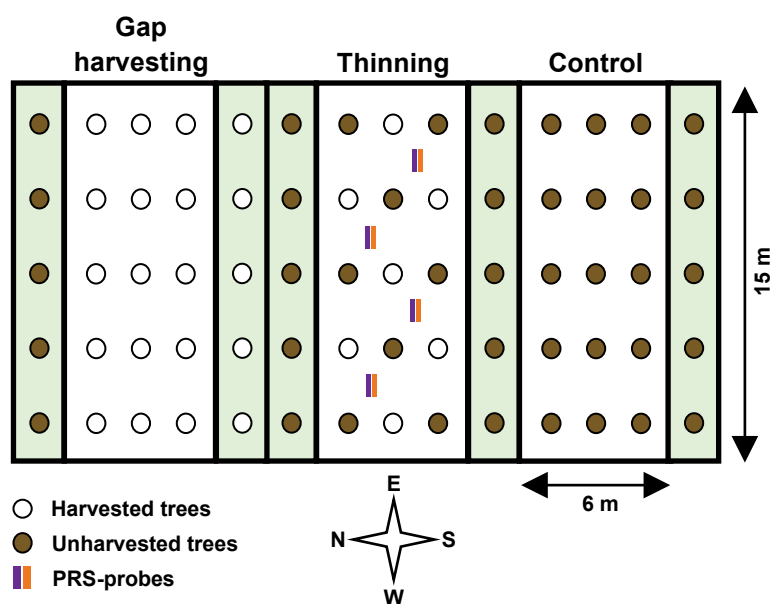
Figure 2. Schematic representation of one block of the experimental design with the three harvesting treatment plots (white rectangle) separated by buffer rows (green rectangles). Prior to applying the harvesting treatments at the end of the seventh growing season, each plot contained 15 trees planted with a 2 × 3 m spacing (1666 trees/ha). The hybrid poplar bioenergy buffer width is 15 m. PRS probe placement locations within all plots are shown in the thinning treatment.

One unharvested buffer row was left between plots of the different harvesting treatments to minimize interference between treatments. An additional buffer row, where all trees were harvested, was left at the margin of the gap harvesting treatment to create larger canopy openings (i.e., 8 m × 15 m or 120 m^2). However, it was impossible to have two thinned buffer rows bordering the thinning treatment due to space limitations. Thus, in its broader context, the thinning treatment does not represent a true 50% thinning but a thinning intensity of 28% (i.e., 7 harvested trees out of 25 trees) (Figure 2). During the postharvest years, shoots growing from cut stumps in the gap harvesting treatment were not thinned to retain the dominant shoot as previous studies have shown no positive effect of such a treatment on the height and diameter growth of the dominant shoot [56].

2.3. Tree Characteristics and Stand Productivity in Thinning and Control Treatments

At the end of the 7th, 8th, 9th, and 10th growing seasons (October 2017–2020), DBH values at 1.3 m from ground level were recorded for each tree in all plots of the thinning and control treatments. DBH data were then used to estimate stem volume and aboveground woody biomass of each tree using allometric relationships. The selected relationships were developed using eight-year-old trees from the same bioenergy buffers but planted with other genotypes in a neighbouring experimental design with the same spacing and buffer width [37]. Relationships developed for genotype M×B-915311, a *P. maximowiczii × Populus balsamifera* L. hybrid, were used to estimate volume and biomass of genotype DN×M-915508 as both of these genotypes were shown to have very similar biomass and volume allometry in plantations and linear buffer strips [44,53]. Stem quality and stand productivity were evaluated when thinning was conducted (after seven years) and during three consecutive post-thinning years (after 8 to 10 years). A 100% survival rate was achieved in all thinned and control plots during the study duration, so this variable was not analyzed.

2.4. Shoot Growth from Cut Stumps in the Gap Harvesting Treatment

In the gap harvest treatment, we evaluated to what extent poplars regrow from cut stumps. In late September of the second postharvest growing season (2019), we measured

stump survival (i.e., stumps with at least one living shoot), the number of shoots above the browse line, and the height of the tallest shoot for stumps having at least one shoot above the browse line. The browse line was set at 1.75 m in height from ground level based on observations from white-tailed deer browsing in the Province of Québec [57]. These variables were not measured on stumps of the thinned plots as shoot development was marginal under the poplar canopy.

2.5. Soil Element Availability and Microclimatic Conditions

Soil temperature and relative moisture content were measured twice during the first postharvest year (8th growing season), on 16 July and 24 August 2018, and once during the second postharvest year (9th growing season), on 27 June 2019. In each plot, temperature and moisture content were measured three times (triplicate sampling) by inserting a T350 Aquaterr soil probe (Costa Mesa, CA, United States) in the 0–15 cm soil layer (Costa Mesa, CA, United States). All measurements were taken between 11h00 and 14h00 when the weather was sunny or partly sunny. Canopy openness was measured on 23 August 2018, during the first postharvest. Hemispherical photographs were taken 1 m above the ground level in the centre of each plot. The software Gap Light Analyzer V 2.0 (Simon Fraser University, Burnaby, BC, Canada) was used to compute canopy openness values from hemispherical photographs.

Soil nutrient and metal availability were measured using Plant Root Simulator Probes (PRS^{TM}-Probes) from Western Ag Innovations Inc., Saskatoon (SK), Canada. This technology consists of ion exchange membranes (adsorbing surface area of 17.5 cm^2/probe) encapsulated in thin plastic probes inserted with little disturbance into the A horizon (0–10 cm layer). PRS probes then adsorb nutrients and metals in their available forms during the burial period. Each pair of probes have an anion and a cation exchange membrane. Strong and significant correlations between nutrient supply rates measured with PRS probes and soil nutrient concentrations or stocks measured using conventional extraction methods were observed at other hybrid poplar buffer sites of southern Québec [52].

During the first (2018) and second (2019) postharvest growing season (i.e., eighth and ninth growing seasons), available macronutrients (NO$_3$, NH$_4$, P, K, Ca, Mg, S), micronutrients (Fe, Mn, Cu, Zn, B), and metals (Al, Pb, and Cd) supply rates were measured in each plot. A composite sample was used in each plot, with four pairs of probes being inserted in the soil (see Figure 2 for probe placement within a plot). PRS probes were buried in the soil for 54 days (7 June–31 July) in 2018 and 59 days (26 May–22 July) in 2019. Once removed from the soil, probes were washed with distilled water and sent back to the Western Ag lab for analysis.

2.6. Statistical Analyses

The harvesting treatment effect on soil and canopy data was analyzed with a one-way ANOVA in a fixed factorial design (3 harvesting treatments × 5 blocks). For tree and stand productivity data, only the control and thinning treatments were considered in the ANOVA (2 harvesting treatments × 5 blocks). The spatial effect on poplar tree growth in unharvested control plots was tested with a one-way ANOVA using tree row in the buffer as a fixed factor (5 rows × 5 blocks). For all ANOVAs, each sampling period or year was analyzed separately.

Following all ANOVAs, the normality of the distribution of the residuals was verified using the Shapiro–Wilk W-test. Some nutrient availability variables did not meet the assumption of normality in residuals distribution during the first postharvest year and were transformed using a logarithmic (ln) or a square root transformation [58]. No statistical analysis was performed on soil Cd supply rates as these were almost always below the detection limit. All statistical analyses were performed using JMP (version 11) of the SAS Institute (Cary, NC, United States).

3. Results

3.1. Effects of Thinning on Tree and Stand Growth

Poplar DBH and stem volume in the thinned plots respectively increased from 13.1 cm to 18.6 cm and from 92.1 to 218 dm^3 over a three-year period, which contrasts with the smaller growth increases observed on stems of the control plots (DBH increase from 13.0 cm to 16.6 cm and stem volume increased from 91.9 to 168 dm^3) (Figure 3a,b). At the end of the third post-thinning year, DBH and individual stem volume were respectively 12% and 30% higher in the thinned plots compared with the control plots, and the harvesting treatment effect was highly significant ($p \leq 0.001$).

At the beginning of the trial (after seven years), productivity was not statistically different between thin and unthinned plots ($p = 0.29$) (Figure 3c–f). However, at the end of the trial (after ten years), a highly significant harvesting treatment effect ($p = 0.008$) was observed on stand volume, stand woody biomass, and stand productivity, with thinned plots being 9% less productive than unthinned plots. Both thinned and unthinned plots also showed an increase in mean annual increment (i.e., volume or biomass yields) during the three years that followed the thinning treatment conducted after seven years (Figure 3e,f), but control plots showed the largest increases.

More specifically, from the end of the 7th growing season to the end of the 10th growing season, total stand volume increased from 153 m^3/ha to 281 m^3/ha (a 128 m^3/ha gain) in control plots and from 145 m^3/ha to 257 m^3/ha (a 112 m^3/ha gain) in thinned plots (Figure 3c,d). The productivity gap also widened over the years between the control and thinned plots (7.7 m^3/ha after 7 years; 15.6 m^3/ha after 8 years, 20.6 m^3/ha after 9 years; 23.4 m^3/ha after 10 years). During this period, the standing volume (i.e., the volume of remaining trees) more than doubled in the thinning treatment (82 m^3/ha after 7 years vs. 194 m^3/ha after 10 years). However, the difference in current annual increment (CAI) for standing volume between thinned and control plots narrowed over the years, with the treatment effect being nonsignificant on CAI during the 9th year ($p = 0.06$) and 10th year ($p = 0.20$) (i.e., second and third post-thinning growing seasons) (Table 1).

Table 1. Harvesting treatment effect on the current annual increment (CAI) for stand volume during the 8th, 9th and 10th growing seasons in the hybrid poplar bioenergy buffers. SE represents the standard error of the mean.

	Current Annual Increment for Stand Volume (m^3/ha)		
Treatment	8th	9th	10th
Control	44.8	36.6	46.2
Thinning	36.9	31.7	43.4
SE	0.8	1.4	1.3
p value	0.003	0.06	0.20

3.2. Poplar Regrowth from Cut Stumps in the Gap Harvesting Treatment

Two years after tree harvesting, the regrowth of poplars from stumps was irregular across blocks and stump death (i.e., stumps with no living shoots) of up to 27% was observed (Table 2). Also, not all stumps that were alive had shoots above the browse line (i.e., shoot height > 1.75 m) after two years of regrowth. On average, 67% of stumps had grown shoots above the browse line, and no shoot above 3 m in height was observed across blocks. Overall, due to the heavy deer browsing observed on poplar shoots growing from stumps, stand regeneration was irregular in the gap harvesting treatment (Figure 4).
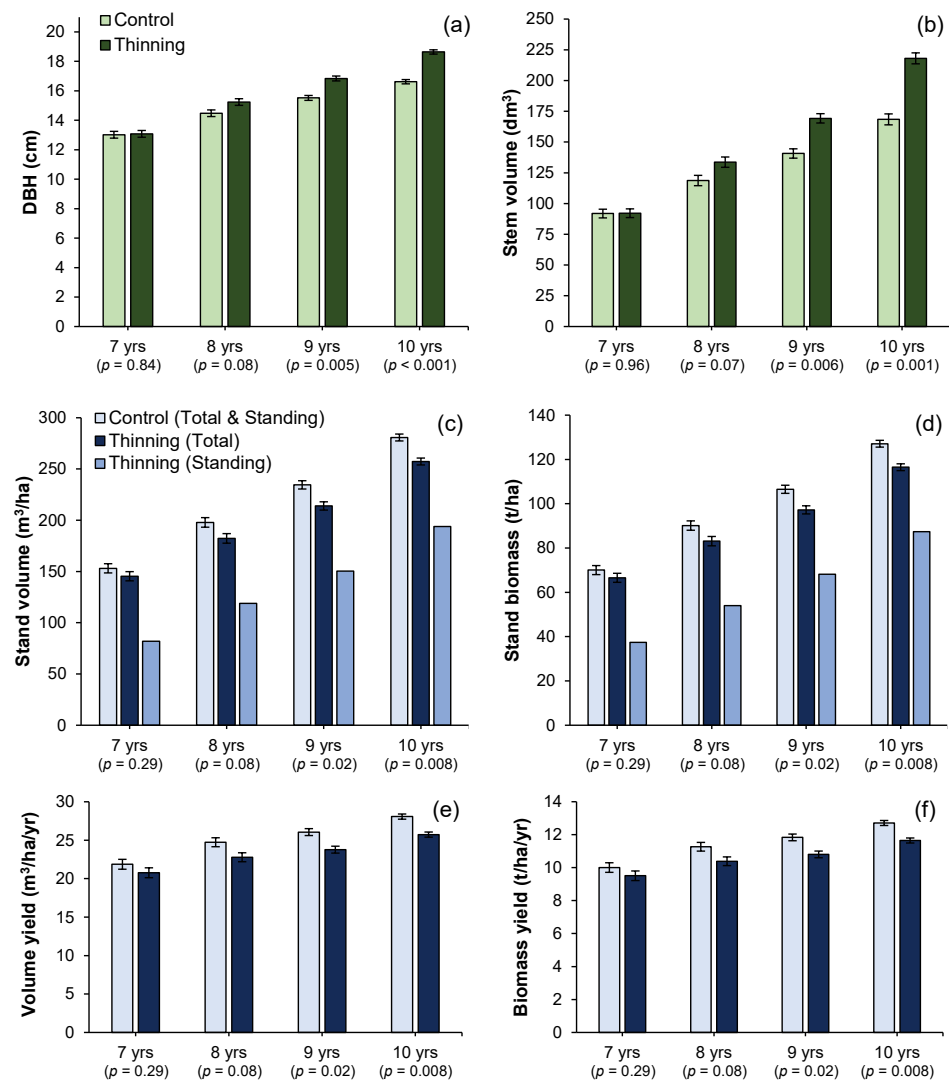
Figure 3. Harvesting treatment effect on (**a**) diameter at breast height (DBH), (**b**) stem volume per tree, (**c**) total stand volume produced, (**d**) total stand woody aboveground biomass produced, (**e**) volume yield and (**f**) aboveground woody biomass yield in hybrid poplar bioenergy buffers after 7 to 10 years of growth. The thinning treatment was performed at the end of the seventh growing season. The *p* value of the treatment effect is indicated, and vertical bars represent standard errors of the mean for each growing season. In panels (**c**,**d**), the standing volume or standing biomass remaining after the thinning treatment is presented. These variables were not used in the ANOVA.

Table 2. Interblock variation in the stump and shoots characteristics at the end of the second postharvest year in the gap harvest treatment.

Block	Stumps with Living Shoots (%)	Stumps with Shoots >1.75 m Tall (%) [1]	Shoots with Height >1.75 m (n/stump)	Maximum Shoot Height (cm)
B1	87	73	7	257
B2	87	73	5	270
B3	73	60	2	210
B4	80	33	4	225
B5	93	93	6	295
Mean	84	67	5	252

[1] The height of 1.75 m refers to the browse line of the white-tailed deer in this study.

(a)　　　　　　　　　　　　　　　　　　(b)
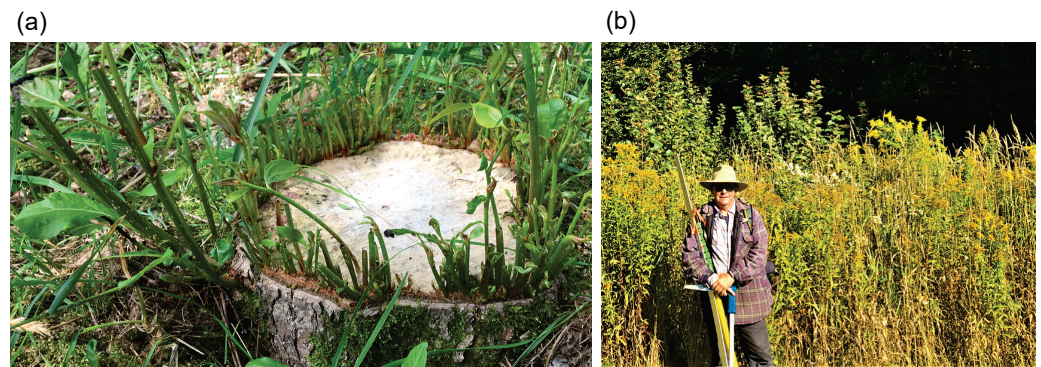
Figure 4. Heavy deer browsing on shoots growing from cut stumps (**a**) have led to irregular stand regeneration in the gap harvesting treatment after the second postharvest year (**b**).

3.3. Spatial Pattern of Tree Growth in Control Plots

A significant spatial effect was observed on DBH and individual stem volume across the study period, with an increase in the significance level of the spatial effect over the years (from $p = 0.02$ after 7 years to $p < 0.001$ after 10 years) (Figure 5). The highest DBH and stem volume values were generally observed in the rows closest to the hayfield (rows 1 and 2), while the middle row of the buffer (row 3) showed the lowest values. Edge rows (row 1 and row 5) also experienced the largest gain in DBH and stem volume during the study period. In three years, individual stem volume increased from 125 to 267 dm^3 in row 1, from 81 to 173 dm^3 in row 5, but only from 68 to 106 dm^3 in row 3. Consequently, after 10 years, DBH and stem volume of trees in row 1 were respectively 54% and 152% higher than what was observed for trees in row 3.

3.4. Harvesting Treatment Effects on Soil Element Availability and Microclimate

Significant harvesting treatment effects were observed on many soils and microclimatic variables (Table 3). The highest soil temperature, soil moisture content, and canopy openness values were generally observed in the gap harvesting treatment during both postharvest years. During the first postharvest year, the availability of several soil elements was the lowest in the control treatment and the highest in the gap harvesting treatment, while K availability followed the opposite pattern. However, during the first postharvest year, the harvesting treatment effect was not significant on the availability of most limiting nutrients ($p = 0.21$ for NO$_3$, $p = 0.84$ for NH$_4$ and $p = 0.21$ for P), despite the high soil NO$_3$ and P supply rates observed in the gap treatment.

During the second postharvest year, almost all soil elements were not significantly affected by harvesting treatments, with soil NO$_3$ being the exception ($p = 0.003$). Anespecially low supply rate of NO$_3$ was observed in the gap harvesting treatment (2.4 µg/10 cm^2/59 days) compared with the thinning (13.0 µg/10 cm^2/59 days) and control (19.3 µg/10 cm^2/59 days) treatments.
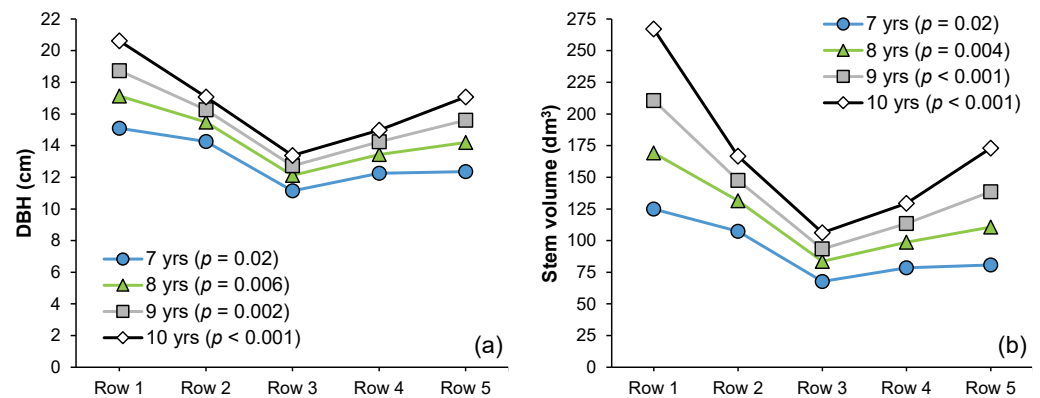
Figure 5. Spatial effect on (**a**) diameter at breast height (DBH) and (**b**) stem volume per tree in the control treatment (no harvest) of the hybrid poplar bioenergy buffers. The legend indicates the *p* value of the spatial effect for the different plantation ages. Standard errors of the mean for the different plantation ages are the following: ± 0.8 cm and ± 12 dm^3 (7 years); ± 0.8 cm and ± 14 dm^3 (8 years); ± 0.8 cm and ± 15 dm^3 (9 years); ± 0.9 cm and ± 17 dm^3 (10 years). Row 1 borders the hayfields.

Table 3. Harvesting treatment effect on canopy openness, soil microclimate and soil element availability in hybrid poplar bioenergy buffer strips during the first (2018) and second (2019) postharvest years. Soil element availability was measured using PRS probe ion-exchange membranes for 54 days in 2018 (7 June–31 July) and 59 days in 2019 (26 May–22 July). Units of soil element availability are μg/10 cm^2/54 or 59 days. SE represents the standard error of the mean, and *p* values in bold indicate a significant harvesting treatment effect.

Postharvest Year (Poplar Age)	Buffer Characteristics	Control	Thinning	Gap	SE	*p* Value
First (8 years old)	Canopy openness–August 23 (%)	4.9	14.5	66.8	2.4	**<0.0001**
	Moisture (%)–July 16 (%)	68.9	70.7	81.4	2.5	**0.01**
	Temperature–July 16 (°C)	22.4	23.1	24.7	0.2	**0.0003**
	Moisture (%)–August 24 (%)	80.9	80.4	91.5	1.4	**0.0008**
	Temperature–August 24 (°C)	21.1	21.1	21.2	0.3	0.97
	NO$_3$	14.3	23.1	55.5	15.7	0.21
	NH$_4$	1.95	2.01	2.17	0.28	0.84
	P	4.45	4.78	6.46	0.78	0.21
	K	77.3	58.3	12.5	14.7	**0.04**
	Ca	1464	2140	2560	84	**<0.0001**
	Mg	286	402	371	16	**0.003**
	S [1]	14.5	34.1	59.3	13.9	**0.02**
	B	0.82	0.86	0.87	0.23	0.99
	Mn [1]	0.9	2.7	39.2	12.4	**0.003**
	Fe [1]	4.0	8.5	218.4	81.7	**0.001**
	Cu [2]	0.10	0.35	2.27	0.39	**0.0004**
	Zn [1]	0.35	0.62	2.92	0.42	**0.0001**
	Al	15.5	18.7	18.3	2.6	0.65
	Pb [2]	0.02	0.36	3.18	0.61	**0.0005**

Table 3. *Cont.*

Postharvest Year (Poplar Age)	Buffer Characteristics	Control	Thinning	Gap	SE	*p* Value
Second (9 years old)	Moisture (%)–June 27	79.4	80.7	88.5	2.0	**0.02**
	Temperature (°C)–June 27	19.5	19.0	21.7	0.3	**0.0005**
	NO_3	19.3	13.0	2.5	2.4	**0.003**
	NH_4	2.57	2.70	2.21	0.31	0.55
	P	6.4	8.4	10.9	2.1	0.37
	K	15.1	16.7	11.2	3.1	0.48
	Ca	2491	2444	2680	88	0.19
	Mg	354	364	351	17	0.86
	S	34.4	51.8	33.2	9.8	0.37
	B	0.28	0.39	0.32	0.13	0.87
	Mn	74	68	116	21	0.26
	Fe	231	172	300	69	0.46
	Cu	2.25	2.49	2.61	0.35	0.76
	Zn	2.19	2.43	3.97	0.64	0.17
	Al	14.7	17.4	14.1	1.3	0.24
	Pb	3.56	3.37	3.82	0.51	0.82

[1] Data were log-transformed prior ANOVA. [2] Data were square-root-transformed prior ANOVA.

4. Discussion

Despite the increasing interest in planting bioenergy buffers in agroecosystems worldwide [1,5,10,12,15], very few studies have evaluated how the management of these buffers would affect soil characteristics and biomass or timber production. Here we showed that seven-year-old hybrid poplar bioenergy buffers planted with a 1666 trees/ha density had a strong growth response to a thinning treatment carried out after canopy closure (Figure 3). Loss of stand productivity was also relatively small, three years after thinning (Figure 3). Additionally, thinning had only marginal effects on soil nutrient availability and soil microclimate of the buffers, compared with gap harvesting (Table 3). This later treatment was also ineffective in regenerating the buffers adequately with shoots growing from cut stumps, mainly because of the high deer browsing in the study area (Table 2, Figure 4). Finally, a strong spatial pattern in tree growth characterized the studied buffers (Figure 5). These results confirm our hypothesis and have important management implications for the multi-functionality of bioenergy buffers in agricultural landscapes.

In the thinning treatment, we removed the equivalent of 63 m^3/ha (i.e., 43% of the standing volume) after seven years. This induced a fast and large growth response at the tree level with a 30% increase in individual stem volume after the third post-thinning year. Such a growth response to thinning is characteristic of other fast-growing species (e.g., eucalyptus) planted on high fertility sites [24]. However, despite this significant increase in the growth rate of individual trees in thinned plots, stand productivity was slightly lower (by 9%) in the thinning treatment after the third post-thinning year (Figure 3), as seen in moderately thinned hybrid aspen stands planted on former agricultural land of Sweden [31]. Sill, given the trend observed in CAI at the stand level (Table 1), it is possible that the productivity gap between thinned and control plots will narrow, or even disappear, past the 10th growing season.

Given the strong response of hybrid poplar to thinning, there would be several advantages in using partial harvesting treatments over clearcutting in bioenergy buffers. Thinning would allow a more regular supply of biomass through time, which would be more in line with annual needs for firewood to locally heat farm buildings. Also, the longer-term resilience of tree buffers may be improved following thinning as larger diameter hybrid poplars are less vulnerable to wind or ice storms [20]. These larger diameter trees could eventually be marketed for the production of sawlogs and veneer, but early and periodic pruning may be required, especially in edge rows of the buffer [15,34]. Such a production strategy would have two positive outcomes for C storage: (1) longer-term

C storage in durable solid wood products vs. the sole use of poplar for bioenergy [7], and (2) an extended rotation length which is required to produce sawlogs of satisfactory diameter [21,59]. Compared with the gap harvesting or clearcutting, thinning in bioenergy buffers would also maintain a more uniform tree canopy and forest structure over the years, which is important for providing microclimatic and habitat functions associated with forest corridors in agricultural landscapes [9].

For the duration of the study, yields increased in thinned, and control plots and overall productivity of the buffers was relatively high in both thinned (25.7 m^3/ha/y) and unthinned (28.1 m^3/ha/y) plots after 10 years of growth (Figure 3e,f). Yields within that range or higher were equally observed after nine years in narrower poplar riparian buffers planted on pastures and hayfields of southern Québec [52], confirming the potential of those agroforestry systems as a sustainable and highly productive source of biomass in the region. Biomass yield and CAI results also suggest that both thinned and unthinned hybrid poplar buffers maintain a very high C sequestration rate compared with other plantation types and natural forests in the study region [8,60]. Thus, hybrid poplar should be preferred to other tree species where the goal is to maximize short-term C storage in agroforestry systems of Southeastern Canada. The high biomass productivity of poplar buffers could also generate leverage to reduce wood harvest pressure in farmland woodlots and create regional opportunities to protect natural forests, thereby increasing their C storage capacity [7,8]. The productivity of the studied genotype (DN×M-915508) was also similar to other genotypes (M×B-915311 and D×N-3570) planted in the same conditions in other experimental bioenergy buffers at the study site [37]. However, those genotypes should also be tested in thinning trials conducted after canopy closure since poplar species such as *P. deltoides* can respond poorly to thinning following crowding [34].

Heavy deer browsing at the study site may not be the sole explanation for the poor regrowth of poplar shoots from cut stumps (Table 2, Figure 4). Because of the low shade tolerance of poplars, it is also possible that the size of gaps used in this study was too small to obtain a high growth rate of shoots growing from stumps. This could have magnified the impact of herbivory on stand regeneration following gap harvesting. In the study area, poplar buffer regrowth from cut stumps needs to be evaluated following larger gap harvests and clearcutting in larger-scale plantings, which would dilute deer browsing effects on shoots growing from stumps. Other thinning patterns and intensities may also be evaluated, including corridor thinning, which was successfully used in hybrid aspen coppices [33]. Given that trees from the middle row of the buffer experienced a low growth rate from the end of the 7th to the end of the 10th growing season (Figure 5), they could be all harvested after seven years to stimulate the growth of trees located in adjacent interior rows.

As expected, the spatial pattern observed in tree growth between rows of the buffer suggests a fertilizing effect of the hayfields on poplars, as trees from rows 1 and 2 were generally larger than trees located in row 5, the other edge row of the buffer (Figure 5). As shown in a willow buffer, N loading by enriched groundwater has a positive effect on tree growth and nutrient storage in biomass of the first two rows facing cultivated land [12]. However, due to greater access to light, trees from row 5 will eventually outgrow trees from row 2. Because of their higher growth rate, trees in edge rows could be the last to be harvested if corridor or row thinning were to be implemented in bioenergy buffers.

As seen in other studies [18,39–41], harvesting treatments not only modify stand structure, they also significantly affect microclimate and soil nutrient availability (Table 3). During the first postharvest year, the more intensive treatment (i.e., gap harvesting) was generally associated with the highest availability of soil elements, the highest soil moisture content, and the highest soil temperatures, as thinning effects on soil were weaker. The complete removal of tree biomass in the gap harvest treatment has likely led to a reduction in soil water and nutrient uptake by trees, but also a reduction in rainfall interception, especially considering the low shoot regrowth from cut stumps observed [61]. Concurrently, higher soil water content and temperatures under canopy gaps potentially enhance soil

organic matter mineralization and release of nutrients and metals in soil, as seen in intensively thinned poplar plantations [40]. Soil K availability followed a completely different pattern since it was the lowest under canopy gaps and highest in control plots during the first postharvest year. Such a result is consistent with the fact that most stand deposition of K originates from canopy leaching in mature poplar plantations [62].

One of the objectives of bioenergy buffers planted along cultivated fields is to reduce N and P loads to streams or groundwater. Intensive tree harvesting treatments (clearcutting and large gap harvests) are generally known to contribute more to NO_3 leaching than extensive tree harvesting treatments such as thinning [17]. However, in this study, effects of harvesting on soil element availability were of short duration as they were mostly observed during the first postharvest year (Table 3). Surprisingly, soil NO_3 availability was the lowest in the gap harvest treatment during the second postharvest year despite the opposite trend having been observed during the first postharvest year (Table 3). The vigorous growth of the herbaceous layer under canopy gaps (Figure 4) combined with the loss of N inputs from leaf litter fall in the gap harvesting treatment may have contributed to such results during the second postharvest year.

Moreover, we felled trees with a chainsaw and transported woody biomass manually out of the plots, which created very little disturbance of the soil in the harvesting treatments. Completely different harvest effects on soil nutrients may have been obtained if an operational harvest had been carried out with heavy machinery. In such a context, a frozen ground harvest would be recommended to minimize soil disturbance [63], especially for bioenergy buffers planted in agricultural riparian zones.

5. Conclusions

This study showed a strong and rapid growth response of seven-year-old hybrid poplar trees to thinning (diamond pattern of tree removal) carried out after canopy closure in wide hybrid poplar bioenergy buffers planted along the hayfields. Unfortunately, gap harvesting was not an effective treatment to regenerate the stand from shoots growing from cut stumps because of the high deer browsing at the site. Overall, thinning had marginal effects on soil nutrient availability and soil microclimate, compared with gap harvesting. However, harvest effects on soil nutrients were mostly observed during the first postharvest year. The spatial pattern observed in tree growth between the rows of the buffer suggests that other more operational thinning patterns (i.e., row or corridor thinning) need to be evaluated for their effects on stand productivity and the provision of ecosystem services. A better understanding of the trade-offs between biomass production, using different harvesting scenarios, and nontimber ecosystem services is clearly needed to more efficiently manage upland and riparian bioenergy buffers as multifunctional elements of agricultural landscapes [10,64].

The growth response of other hybrid poplar genotypes and genomic groups to harvesting treatments should also be evaluated alongside the longer-term stability and productivity of thinned vs. unthinned poplar buffers. Such information will help in managing those agroforestry systems for maximum C storage. From a forest restoration perspective, partial harvesting treatments can also create opportunities to underplant valuable tree species adapted to shelterwood environments (e.g., *Quercus rubra* L., *Pinus strobus* L., *Carya cordiformis* (Wangenh.) K. Koch, *Juglans nigra* L.) and to retain coarse woody debris in the understory [8,65]. Agricultural buffers that are more similar to natural forests, having a more diversified stand structure and species composition, but also a longer-term C storage potential, could then be created to complement the intensively managed poplar buffers.

References

1. Dal Ferro, N.; Borin, M.; Cardinali, A.; Cavalli, R.; Grigolato, S.; Zanin, G. Buffer strips on the low-lying plain of Veneto region (Italy): Environmental benefits and efficient use of wood as an energy resource. *J. Environ. Qual.* **2019**, *48*, 280–288. [CrossRef] [PubMed]
2. Ferrarini, A.; Serra, P.; Almagro, M.; Trevisan, M.; Amaducci, S. Multiple ecosystem services provision and biomass logistics management in bioenergy buffers: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2017**, *73*, 277–290. [CrossRef]
3. Fortier, J.; Truax, B.; Gagnon, D.; Lambert, F. Biomass carbon, nitrogen and phosphorus stocks in hybrid poplar buffers, herbaceous buffers and natural woodlots in the riparian zone on agricultural land. *J. Environ. Manag.* **2015**, *154*, 333–345. [CrossRef]
4. Fortier, J.; Truax, B.; Gagnon, D.; Lambert, F. Soil nutrient availability and microclimate are influenced more by genotype than by planting stock type in hybrid poplar bioenergy buffers on farmland. *Ecol. Engin.* **2020**, *157*, 105995. [CrossRef]
5. Hénault-Ethier, L.; Gomes, M.P.; Lucotte, M.; Smedbol, É.; Maccario, S.; Lepage, L.; Juneau, P.; Labrecque, M. High yields of riparian buffer strips planted with *Salix miyabena* 'SX64' along field crops in Québec, Canada. *Biomass Bioenergy* **2017**, *105*, 219–229. [CrossRef]
6. Fortier, J.; Gagnon, D.; Truax, B.; Lambert, F. Understory plant diversity and biomass in hybrid poplar riparian buffer strips in pastures. *New For.* **2011**, *42*, 241–265. [CrossRef]
7. 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.; et al. A synthesis of current knowledge on forests and carbon storage in the United States. *Ecol. Appl.* **2011**, *21*, 1902–1924. [CrossRef]
8. Fortier, J.; Truax, B.; Gagnon, D.; Lambert, F. Potential for hybrid poplar riparian buffers to provide ecosystem services in three watersheds with contrasting agricultural land use. *Forests* **2016**, *7*, 37. [CrossRef]
9. Bentrup, G. *Conservation Buffers: Design Guidelines for Buffers, Corridors, and Greenways*; US Department of Agriculture, Forest Service, Southern Research Station: Asheville, NC, USA, 2008; p. 110.
10. Englund, O.; Börjesson, P.; Mola-Yudego, B.; Berndes, G.; Dimitriou, I.; Cederberg, C.; Scarlat, N. Strategic deployment of riparian buffers and windbreaks in Europe can co-deliver biomass and environmental benefits. *Commun. Earth Environ.* **2021**, *2*, 176. [CrossRef]
11. Bedard-Haughn, A.; Tate, K.W.; van Kessel, C. Quantifying the impact of regular cutting on vegetative buffer efficacy for nitrogen-15 sequestration. *J. Environ. Qual.* **2005**, *34*, 1651–1664. [CrossRef]
12. Ferrarini, A.; Fornasier, F.; Serra, P.; Ferrari, F.; Trevisan, M.; Amaducci, S. Impacts of willow and miscanthus bioenergy buffers on biogeochemical N removal processes along the soil–groundwater continuum. *GCB Bioenergy* **2017**, *9*, 246–261. [CrossRef]
13. Butler, B.J.; Hewes, J.H.; Dickinson, B.J.; Andrejczyk, K.; Butler, S.M.; Markowski-Lindsay, M. Family forest ownerships of the United States, 2013: Findings from the USDA Forest Service's national woodland owner survey. *J. For.* **2016**, *114*, 638–647. [CrossRef]
14. Côté, M.-A.; Gilbert, D.; Nadeau, S. Characterizing the profiles, motivations and behaviour of Quebec's forest owners. *For. Policy Econ.* **2015**, *59*, 83–90. [CrossRef]
15. Johnson, J.D.; Henri, C.J. Riparian forest buffer income opportunities: A hybrid poplar case study. *J. Soil Water Conserv.* **2005**, *60*, 159–163.
16. Brown, G.W.; Krygier, J.T. Effects of clear-cutting on stream temperature. *Water Resour. Res.* **1970**, *6*, 1133–1139. [CrossRef]
17. Prescott, C.E.; Hope, G.D.; Blevins, L.L. Effect of gap size on litter decomposition and soil nitrate concentrations in a high-elevation spruce fir forest. *Can. J. For. Res.* **2003**, *33*, 2210–2220. [CrossRef]
18. James, J.; Harrison, R. The effect of harvest on forest soil carbon: A meta-analysis. *Forests* **2016**, *7*, 308. [CrossRef]
19. Bliss, J.C. Public perceptions of clearcutting. *J. For.* **2000**, *98*, 4–9.

20. Van Oosten, C. *Hybrid Poplar Crop Manual for the Prairie Provinces*; SilviConsult Woody Crops Technology Inc.: Nanaimo, BC, Canada, 2006; p. 232.
21. Stanton, B.; Eaton, J.; Johnson, J.; Rice, D.; Schuette, B.; Moser, B. Hybrid poplar in the pacific northwest: The effects of market-driven management. *J. For.* **2002**, *100*, 28–33.
22. Christersson, L. Wood production potential in poplar plantations in Sweden. *Biomass Bioenergy* **2010**, *34*, 1289–1299. [CrossRef]
23. Stanturf, J.A.; van Oosten, C. Operational poplar and willow culture. In *Poplars and Willows: Trees for Society and the Environment*; Isebrands, J.G., Richardson, J., Eds.; CABI: Wallingford, UK; FAO: Rome, Italy, 2014; pp. 200–257.
24. Forrester, D.I. Growth responses to thinning, pruning and fertiliser application in Eucalyptus plantations: A review of their production ecology and interactions. *For. Ecol. Manag.* **2013**, *310*, 336–347. [CrossRef]
25. Sword Sayer, M.A.; Goelz, J.C.G.; Chambers, J.L.; Tang, Z.; Dean, T.J.; Haywood, J.D.; Leduc, D.J. Long-term trends in loblolly pine productivity and stand characteristics in response to thinning and fertilization in the West Gulf region. *For. Ecol. Manag.* **2004**, *192*, 71–96. [CrossRef]
26. Li, Z.; Xiao, J.; Lu, G.; Sun, W.; Ma, C.; Jin, Y. Productivity and profitability of *Larix principis-rupprechtii* and *Pinus tabuliformis* plantation forests in Northeast China. *For. Policy Econ.* **2020**, *121*, 102314. [CrossRef]
27. Forrester, D.I.; Elms, S.R.; Baker, T.G. Tree growth-competition relationships in thinned *Eucalyptus* plantations vary with stand structure and site quality. *Eur. J. For. Res.* **2013**, *132*, 241–252. [CrossRef]
28. Schönau, A.P.G.; Coetzee, J. Initial spacing, stand density and thinning in eucalypt plantations. *For. Ecol. Manag.* **1989**, *29*, 245–266. [CrossRef]
29. Thiffault, N.; Hoepting, M.K.; Fera, J.; Lussier, J.-M.; Larocque, G.R. Managing plantation density through initial spacing and commercial thinning: Yield results from a 60-year-old red pine spacing trial experiment. *Can. J. For. Res.* **2020**, *51*, 181–189. [CrossRef]
30. Liechty, H.O.; Mroz, G.D.; Reed, D.D. The growth and yield responses of a high site quality red pine plantation to seven thinning treatments and two thinning intervals. *Can. J. For. Res.* **1986**, *16*, 513–520. [CrossRef]
31. Rytter, L.; Stener, L.-G. Productivity and thinning effects in hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) stands in southern Sweden. *For. Int. J. For. Res.* **2005**, *78*, 285–295. [CrossRef]
32. Telenius, B.F. Stand growth of deciduous pioneer tree species on fertile agricultural land in southern Sweden. *Biomass Bioenergy* **1999**, *16*, 13–23. [CrossRef]
33. Hepner, H.; Lutter, R.; Tullus, A.; Kanal, A.; Tullus, T.; Tullus, H. Effect of early thinning treatments on above-ground growth, biomass production, leaf area index and leaf growth efficiency in a hybrid aspen coppice stand. *BioEnergy Res.* **2020**, *13*, 197–209. [CrossRef]
34. Stanturf, J.A.; van Oosten, C.; Coleman, M.D.; Portwood, C.J. Ecology and silviculture of poplar plantations. In *Poplar Culture in North America*; Dickmann, D.I., Isebrands, J.G., Eckenwalder, J.E., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, USA, 2001; pp. 153–206.
35. Anderson, W.C.; Krinard, R.M. In The investment potential of cottonwood sawtimber plantations. In Proceedings of the Third Biennial Southern Sylvicultural Research Conference, Atlanta, GA, USA, 7–8 November 1985; Shoulders, E., Ed.; USDA Forest Service: Atlanta, GA, USA; pp. 190–197.
36. Kern, C.C.; Burton, J.I.; Raymond, P.; D'Amato, A.W.; Keeton, W.S.; Royo, A.A.; Walters, M.B.; Webster, C.R.; Willis, J.L. Challenges facing gap-based silviculture and possible solutions for mesic northern forests in North America. *For. Int. J. For. Res.* **2017**, *90*, 4–17. [CrossRef]
37. Truax, B.; Fortier, J.; Gagnon, D.; Lambert, F. Long-term effects of white-tailed deer overabundance, hybrid poplar genotype and planting stock type on tree growth and ecosystem services provision in bioenergy buffers. *For. Ecol. Manag.* **2021**, *480*, 118673. [CrossRef]
38. Truax, B.; Gagnon, D.; Fortier, J.; Lambert, F. Yield in 8 year-old hybrid poplar plantations on abandoned farmland along climatic and soil fertility gradients. *For. Ecol. Manag.* **2012**, *267*, 228–239. [CrossRef]
39. Blanco, J.A.; Imbert, J.B.; Castillo, F.J. Nutrient return via litterfall in two contrasting *Pinus sylvestris* forests in the Pyrenees under different thinning intensities. *For. Ecol. Manag.* **2008**, *256*, 1840–1852. [CrossRef]
40. Fang, S.; Lin, D.; Tian, Y.; Hong, S. Thinning intensity affects soil-atmosphere fluxes of greenhouse gases and soil nitrogen mineralization in a lowland poplar plantation. *Forests* **2016**, *7*, 141. [CrossRef]
41. Zhou, T.; Wang, C.; Zhou, Z. Thinning promotes the nitrogen and phosphorous cycling in forest soils. *Agri. For. Meteorol.* **2021**, *311*, 108665. [CrossRef]
42. Gross, C.D.; James, J.N.; Turnblom, E.C.; Harrison, R.B. Thinning treatments reduce deep soil carbon and nitrogen stocks in a coastal Pacific Northwest forest. *Forests* **2018**, *9*, 238. [CrossRef]
43. Jonsson, J.A.; Sigurdsson, B.D. Effects of early thinning and fertilization on soil temperature and soil respiration in a poplar plantation. *Icel. Agric. Sci.* **2010**, *23*, 97–109.
44. Fortier, J.; Gagnon, D.; Truax, B.; Lambert, F. Biomass and volume yield after 6 years in multiclonal hybrid poplar riparian buffer strips. *Biomass Bioenergy* **2010**, *34*, 1028–1040. [CrossRef]
45. Truax, B.; Fortier, J.; Gagnon, D.; Lambert, F. Planting density and site effects on stem dimensions, stand productivity, biomass partitioning, carbon stocks and soil nutrient supply in hybrid poplar plantations. *Forests* **2018**, *9*, 293. [CrossRef]

46. Truax, B.; Gagnon, D.; Lambert, F.; Fortier, J. Multiple-use zoning model for private forest owners in agricultural landscapes: A case study. *Forests* **2015**, *6*, 3614–3664. [CrossRef]

47. Fortier, J.; Truax, B.; Gagnon, D.; Lambert, F. Natural drying and chemical characteristics of hybrid poplar firewood produced from agricultural bioenergy buffers in southern Québec, Canada. *Forests* **2021**, *12*, 122. [CrossRef]

48. Cann, D.B.; Lajoie, P.; Stobbe, P.C. *Études des sols des Comtés de Shefford, Brome et Missisquoi dans la Province de Québec*; Ministère de l'Agriculture: Ottawa, ON, Canada, 1948; p. 80.

49. Robitaille, A.; Saucier, J.-P. *Paysages Régionaux du Québec Méridional*; Les Publications du Québec: Ste-Foy, QC, Canada, 1998; p. 213.

50. Government of Canada. Station Results—1981–2010 Climate Normals and Averages. Available online: http://climate.weather.gc.ca/climate_normals/station_select_1981_2010_e.html?searchType=stnProv&lstProvince=QC (accessed on 11 May 2020).

51. Périnet, P.; Gagnon, H.; Morin, S. *Liste des Clones Recommandés de Peuplier Hybride par Sous-Région Écologique au Québec (Mise à Jour Octobre 2010)*; Direction de la Recherche Forestière, MRN: Québec, QC, Canada, 2010; p. 1.

52. Fortier, J.; Truax, B.; Gagnon, D.; Lambert, F. Mature hybrid poplar riparian buffers along farm streams produce high yields in response to soil fertility assessed using three methods. *Sustainability* **2013**, *5*, 1893–1916. [CrossRef]

53. Truax, B.; Gagnon, D.; Fortier, J.; Lambert, F. Biomass and volume yield in mature hybrid poplar plantations on temperate abandoned farmland. *Forests* **2014**, *5*, 3107–3130. [CrossRef]

54. Government of Canada. Historical Climate Data. Available online: https://climate.weather.gc.ca/index_e.html (accessed on 11 May 2020).

55. Christersson, L. Poplar plantations for paper and energy in the south of Sweden. *Biomass Bioenergy* **2008**, *32*, 997–1000. [CrossRef]

56. Davidson, W.H. Hybrid poplar sprout clumps: Thinning does not improve development. *J. For.* **1983**, *81*, 662–663.

57. Gouvernement du Québec. Animaux Importuns—Dommages Causés par la Faune. Fiches Individuelles D'animaux Importuns. Cerf de Virginie. Available online: https://www3.mffp.gouv.qc.ca/faune/importuns/fiche.asp?fiche=cerf_virginie (accessed on 2 December 2021).

58. Manikandan, S. Data transformation. *J. Pharmacol. Pharmacother.* **2010**, *1*, 126–127. [CrossRef]

59. Pérez-Cruzado, C.; Mansilla-Salinero, P.; Rodríguez-Soalleiro, R.; Merino, A. Influence of tree species on carbon sequestration in afforested pastures in a humid temperate region. *Plant Soil* **2012**, *353*, 333–353. [CrossRef]

60. Dancause, A. *Le Reboisement au Québec*; Les Publications du Québec: Québec, QC, USA, 2008; p. 177.

61. Bethlahmy, N. First year effects of timber removal on soil moisture. *Hydrol. Sci. J.* **1962**, *7*, 34–38. [CrossRef]

62. Meiresonne, L.; Schrijver, A.D.; Vos, B.D. Nutrient cycling in a poplar plantation (*Populus trichocarpa* × *Populus deltoides* 'Beaupré') on former agricultural land in northern Belgium. *Can. J. For. Res.* **2007**, *37*, 141–155. [CrossRef]

63. Abrahamson, L.P.; Robison, D.J.; Volk, T.A.; White, E.H.; Neuhauser, E.F.; Benjamin, W.H.; Peterson, J.M. Sustainability and environmental issues associated with willow bioenergy development in New York (U.S.A.). *Biomass Bioenergy* **1998**, *15*, 17–22. [CrossRef]

64. Stutter, M.I.; Chardon, W.J.; Kronvang, B. Riparian buffer strips as a multifunctional management tool in agricultural landscapes: Introduction. *J. Environ. Qual.* **2012**, *41*, 297–303. [CrossRef] [PubMed]

65. Truax, B.; Gagnon, D.; Fortier, J.; Lambert, F.; Pétrin, M.-A. Ecological factors affecting white pine, red oak, bitternut hickory and black walnut underplanting success in a northern temperate post-agricultural forest. *Forests* **2018**, *9*, 499. [CrossRef]