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Potential for Hybrid Poplar Riparian Buffers to Provide Ecosystem Services in Three Watersheds with Contrasting Agricultural Land Use

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Abstract: In temperate agricultural watersheds, the rehabilitation of tree vegetation in degraded riparian zones can provide many ecosystem services. This study evaluated ecosystem service provision potential following the conversion of non-managed herbaceous buffers to hybrid poplar (*Populus* spp.) buffers in three watersheds (555–771 km^2) of southern Québec (Canada), with contrasting agricultural land uses. To extrapolate services at the watershed level, total stream length where hybrid poplars could be established was calculated using GIS data from hydrological and land cover maps. After nine years, a 100% replacement of herbaceous buffers by hybrid poplar buffers along farm streams could lead to the production of 5280–76,151 tons of whole tree (stems + branches) biomass, which could heat 0.5–6.5 ha of greenhouses for nine years, with the potential of displacing 2–29 million litres of fuel oil. Alternatively, the production of 3887–56,135 tons of stem biomass (fuelwood) could heat 55–794 new farmhouses or 40–577 old farmhouses for nine years. Producing fuelwood in buffers rather than in farm woodlots could create forest conservation opportunities on 300–4553 ha. Replacing all herbaceous buffers by poplar buffers could provide potential storage of 2984–42,132 t C, 29–442 t N and 3–56 t P in plant biomass, if woody biomass is not harvested. The greatest potential for services provision was in the Pike River watershed where agriculture is the dominant land use. A review of the potential services of poplar buffers is made, and guidelines for managing services and disservices are provided.

Keywords: multifunctional agroforestry; biomass bioenergy; woodlot biodiversity conservation; carbon, nitrogen and phosphorus storage; fossil fuel displacement; non-point source pollution; stream network; heating value and efficiency; novel ecosystems; Magog, Eaton and Pike Rivers

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1. Introduction

Despite the relatively small land area they occupy in watersheds, riparian zones have a disproportionate influence on water, solutes and energy fluxes between terrestrial and aquatic environments, making these ecotones biogeochemical hotspots at the landscape level [1–3]. The role of riparian zones as buffers for the mitigation of diverse stream pollutants (nitrogen (N), phosphorus (P), pesticides, harmful bacteria and sediments) generated by agricultural activities has been increasingly acknowledged over the last three decades [4–9]. Riparian ecotones are also keystone landscape elements for aquatic, wetland and terrestrial biodiversity, because they possess distinctive characteristics, such as broad hydrological gradients, frequent disturbances (flood/drought cycles, storm flow, streambank failure) and a generally high level of soil fertility [10]. Thus, the use of riparian buffers for biodiversity enhancement or protection is another important conservation practice in agricultural landscapes. A large body of evidence suggests that riparian forest buffers strongly influence aquatic habitat quality, as they contribute to stream channel formation, bank stability, instream habitat creation, and water temperature regulation [11]. The value for conservation of forested buffers on farmland has also been well established for native plant communities, small mammals, birds, reptiles and amphibians [12–14].

In temperate ecosystems, streamside forests were historically the main interface between upland areas and the aquatic environment. However, many farm streams have completely lost their forest cover, as land owners sought to maximise arable land area. Today, several of these streams are only buffered by a narrow strip of herbaceous vegetation, often dominated by ruderal species and having little conservation value [15,16]. This loss of forest vegetation along farm streams has had an impact on ecosystem functions, processes and biodiversity, thereby reducing the quality and diversity of ecosystem services provided by riparian ecotones and freshwater ecosystems. For example, riparian deforestation in agricultural areas often results in channel narrowing, which leads to a reduction in aquatic habitats and in the instream uptake of agricultural pollutants, such as N [17]. Equally, atmospheric CO_2 mitigation through carbon (C) storage in biomass was found to be 25 times lower in herbaceous dominated riparian zones compared to mature riparian forests of the Coastal plain ecoregion (United States) [18]. Consequently, promoting the protection of streamside forests and forest buffer rehabilitation will not only benefit water quality and biodiversity, but global warming mitigation can also be an outcome, as riparian buffers are increasingly recognised as multifunctional features of agricultural landscapes [19–21].

Allowing forest to re-grow naturally along deforested farmland streams may contribute to restoring some ecosystem services related to riparian buffers. However, there is growing evidence that natural succession along several farm streams has been interrupted, with forest species regeneration being poor or absent, even after decades following livestock exclusion or protection from cultivation [15]. Climate change may also put additional pressure on the riparian ecotones of farmland by increasing the intensity, frequency and duration of natural disturbances, which would be particularly detrimental to already degraded and stressed riparian ecotones and the streams they protect [22]. Consequently, in the absence of adequate rehabilitation strategies, farmland streams and riparian ecotones could be particularly vulnerable to climate change [22].

Many riparian ecotones of agricultural areas have crossed an ecological threshold beyond which the recovery to historical conditions or functions, through natural processes, seems improbable [15]; a situation that poses particular challenges, while providing new opportunities for riparian rehabilitation projects. The interacting effects of natural disturbances, herbivore pressure and human-induced disturbances or stressors (channel straightening, surface and sub-surface drainage, soil cultivation, livestock browsing and trampling, pesticide drift, high nutrient inputs) seriously alter hydrological connectivity, soil biogeochemistry and erosion patterns along riparian zones, which weaken species-environment relationships and affect spatial patterns of plant biodiversity [4,15,23,24]. The creation of novel ecosystems in the riparian zones of farmlands for providing ecosystem services would appear to be a more feasible objective than restoration to historical conditions [25].

One of several possible rehabilitation strategies would be the establishment of multifunctional riparian agroforestry systems with fast-growing hybrid poplars, which are well adapted to various riparian environments and other disturbed sites [26–28]. Such systems have the advantage of restoring a forest cover within a decade, which is beneficial for both animal and plant biodiversity [29–31]. Poplar buffers would also provide the opportunity to produce wood or biomass for heating and create a new sink for atmospheric CO_2 [32–36]. The production of this new woody biomass on farmland could reduce the harvesting pressure on remaining natural woodlots, thereby providing forest conservation opportunities [37,38]. Additionally, because they are high nutrient demanding trees [39], poplars planted in buffers become fast-growing sinks for N and P at the stream/cultivated field interface, which will contribute to reducing NO_3 and P leaching losses from farm fields to streams [35,40].

Although many studies have focused on ecosystem services provided by poplar buffers at the farm-scale over the last two decades [27,30–32,35,40–48], none has quantified the potential of this type of riparian buffer for providing ecosystem services at the watershed scale. Such data are essential, as they will contribute to driving policy changes regarding the management of riparian buffers in agricultural landscapes.

The first objective of this study was to evaluate ecosystem service provision related to the conversion of non-managed herbaceous buffers to hybrid poplar buffers in three watersheds of southern Québec (Canada), with contrasting agricultural land uses. This evaluation only focuses on ecosystem services for which precise data are known: (1) wood and biomass production, which could further be used as residential heat energy or as an alternative to fuel oil for the greenhouse growers industry; (2) C storage in plant biomass; (3) N and P storage in plant biomass; and (4) indirect forest conservation value associated to avoided fuelwood harvest in farmland woodlots. The second objective of this study is to provide an extensive review of the potential ecosystem services and disservices related to the establishment of poplar riparian buffers in agricultural areas. Recommendations to optimise potential services, while mitigating potential disservices, are also provided.

2. Materials and Methods

2.1. Watershed Description and Geographic Information for Non-Forested Stream Length on Farmland

To scale up ecosystem service provision at the watershed level, we studied three watersheds of the southern Québec region (Canada) that represent a gradient in their percentage of agricultural land use, but also a gradient in soil fertility (crop productivity) and climate/elevation [49,50]: (1) the Magog River watershed; (2) the Eaton River watershed; and (3) the Pike River ("Rivière aux Brochets") watershed (Figure 1). The Magog River and Eaton River watersheds belong to the Estrie administrative region of Québec and to the Appalachian geological region [49]. In these watersheds, agricultural activities are concentrated in a few large valleys, although pastures and hayfields (the dominant agricultural land use) are common on the gentle slopes that characterize the landscape of the region [49]. The soils of the Magog River and Eaton River watersheds are mainly characterized by a thick till deposit and both watersheds drain into the Saint-François River, which further drains into the St. Lawrence River [49]. The Magog River watershed is characterized by a continental subhumid moderate climate and a growing season of 180 to 190 days [49]. It is also the case for the western part of the Eaton River watershed, while the eastern part of this watershed (located at higher elevation), is characterized by a continental subpolar subhumid climate and a growing season ranging from 170 to 180 days [49]. The Pike River watershed is situated in the Montérégie administrative region of Québec. Geologically, it is located at the transition zone between the St. Lawrence lowlands and the Appalachians [51]. The topography of the Pike River watershed is nearly flat, the growing season (190–200 days) is longer than in the Magog River and Eaton River watersheds, and annual row crops agriculture is a dominant land use [49]. Most of the Pike River watershed is covered by a thick till surface deposit and its hydrological network drains into Lake Champlain [49]. A continental subhumid moderate climate characterizes this watershed [49].

Data obtained from watershed organisations (COGESAF and *Organisme de bassin versant de la baie Missisquoi*) and the regional offices of the *Ministère de l'Agriculture de l'Agroalimentaire et des Pêcheries du Québec* (MAPAQ) were used in determining the watershed boundaries and in the estimation of the land area covered with annual and perennial crops (including pastures) based on 2014 data. A summary of the watershed area occupied by annual and perennial crops is presented in Table 1.

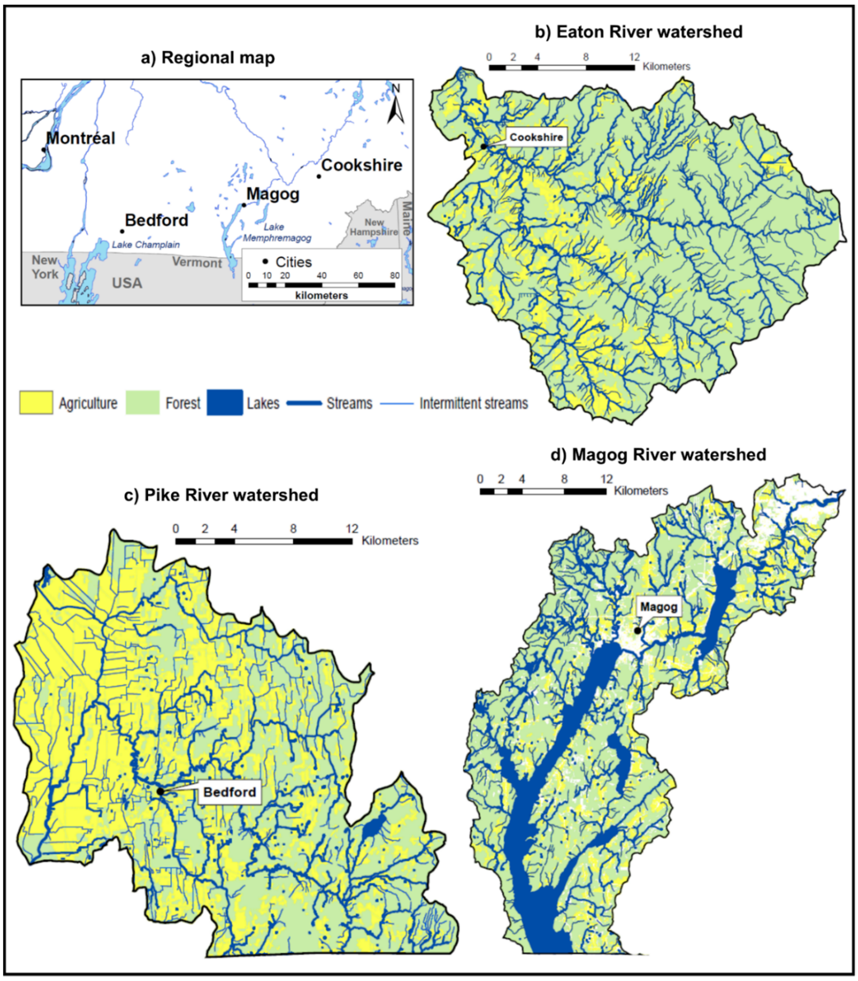


Figure 1. (**a**) Regional map of the study area indicating important cities in the studied watersheds; (**b**–**d**) Maps of the studied watersheds indicating agricultural and forest land use, and hydrological network. Elevation (asl) is 85 m at Bedford, 215 m at Magog and 240 m at Cookshire.

Table 1. Watershed area occupied by annual and perennial crops and pastures in 2014 for the three studied watersheds in Southern Québec.

Watershed	Watershed	Annual Crops		Perennial Crops and Pastures		Total Cultivated Area	
	Area (ha)	ha	%	ha	%	ha	%
Magog River	77,076	681	1	2433	3	3114	4
Eaton River	64,787	2148	3	6403	10	8551	13
Pike River	55,500	17,376	31	8757	16	26,133	47

To extrapolate ecosystem services related to riparian agroforestry systems at the watershed level, we needed to calculate total stream length where hybrid poplars could potentially be established. We assumed that all stream reaches that were not bordered by a forest cover and that were located in the agricultural zone had potential for the implementation of poplar buffers. We also assumed that all those non-forested stream reaches were currently buffered by non-managed herbaceous buffers, which is the most widespread conservation practice in agricultural riparian areas across southern Québec [15]. First, forest cover maps (1:20,000) from the study area were obtained from the *Ministère des Forêts, de la Faune et des Parcs* (Géoboutique Québec, QC, Canada). These forest cover maps were created with the software ArcGIS–Arc MAP 10 provided by Esri (New York, NY, USA). Watershed boundaries were then delineated using geographic information collected from watershed and agricultural land cover, and added to these maps. Thereafter, for each watershed, the geomatic tools of ArcGIS were used to measure the stream length of each perennial and intermittent stream for the entire watershed. The same was done for the length of streams that were only located in the agricultural land cover and not bordered by a riparian forest. These stream length data were cumulated for each of the studied watersheds (Table 2). Determination of perennial and intermittent stream length was based on data from the *Cadre de référence hydrologique du Québec* [52], which excludes ephemeral streams, as well as drainage and road side ditches.

Table 2. Perennial, intermittent and total stream length for the entire watershed and for the agricultural areas (with no riparian forest cover) of three watersheds of Southern Québec.

Watershed	**Perennial stream length**			**Intermittent stream length**			**Total stream length**		
	Watershed (km)	**Agricultural (km)**	**Agricultural (%)**	**Watershed (km)**	**Agricultural (km)**	**Agricultural (%)**	**Watershed (km)**	**Agricultural (km)**	**Agricultural (%)**
Magog River	373	50	13	435	64	15	808	115	14
Eaton River	469	64	14	610	118	19	1080	183	17
Pike River	238	103	43	551	336	61	790	439	56

2.2. Ecosystem Service Provision Related to Increasing Poplar Riparian Agroforestry

2.2.1. Unit Conversion, Timeframe, Agroforestry Model Implemented and Assumptions Related to Site Fertility

Our published data on ecosystem service provision related to the conversion of non-managed herbaceous buffers to hybrid poplar buffers are presented based on a surface area of one hectare [35,42]. The projected poplar agroforestry system that was used for our extrapolations at the watershed level corresponds exactly to the one that was studied at the site level. The buffer strips we planted and studied have a width of 4.5 m on each streambank (3 rows of poplars, parallel to the stream, with a 1.5 m spacing between rows and a 3 m spacing between trees within a row), with an initial density of 2222 stems/ha [35,42]. Consequently, one hectare of hybrid poplar buffer corresponds to a 4.5 m wide buffer that would be established on each streambank along 1.11 km of stream. In other words, a 0.9 ha agroforestry system could be established on each kilometer of non-forested agricultural stream. All the ecosystem services extrapolations to the entire watershed will be based on the following calculations:

$$\text{Watershed ecosystem services} = (\text{Ecosystem services/km of stream}) \times \text{km of stream} \quad (1)$$

Calculations were done for the first poplar rotation, with trees assumed to be harvested after 9 years. Additionally, we assumed that site fertility (or productivity) is expected to vary between the selected watersheds. However, across the same watershed site productivity is assumed to be constant in terms of hybrid poplar growth, and representative of sites for which we have precise data. This assumption is based on the fact that soil types and texture vary little within the agricultural areas of each watershed [51,53,54]. For the Magog River watershed, data collected at the Magog site, a relatively low fertility site, were used for extrapolation [35,42]. For the Eaton River watershed, data from the St-Isidore-de-Clifton site, a moderate fertility site, were used for extrapolation [35,42]. For the Pike River watershed, where row crop agriculture dominates, data from the Brompton site, a high fertility site, were used for extrapolation [35,42]. Across all studied watersheds, agricultural soils are loams (varying from sandy loam to clay loam) [51,53,54], which are ideal for hybrid poplar cultivation [55].

2.2.2. Wood and Woody Biomass Production

Stem wood and woody biomass production services refer to the quantity of stem wood volume (m^3) and the dry aboveground woody biomass that could be produced from poplar riparian buffers based on previous research results obtained after 9 growing seasons in the study area [42]. Wood and biomass production data are mean values obtained from three hybrid poplar clones of different parentages: *Populus deltoides* × *P. nigra* (D × N-3570), *P. maximowiczii* × *P. balsamifera* (M × B-915311) and *P. canadensis* × *P. maximowiczii* (DN × M-915508).

2.2.3. Increase in Carbon, Nitrogen and Phosphorus Storage in Plant Biomass

Carbon, N and P storage services are related to the total stocks of C, N and P that are stored in all biomass components (aboveground, belowground and detrital) of the poplar buffers, minus the C, N and P stocks stored in the different biomass components of non-managed herbaceous buffers. The storage increase values associated to poplar buffer agroforestry were taken from our recent study that was done after 9 growing seasons [35]. Storage increase data are mean values obtained from three hybrid poplar clones of different parentages (see Section 2.2.2).

We did not consider the potential soil C loss or gain associated with poplar agroforestry because the literature suggests that afforestation, with trees from the Salicaceae family, does not produce significant soil C enrichment on a general basis [43,56–61]. However, as part of a land use change process, hybrid polar afforestation on agricultural land can result in soil C loss, on the short-term, but, on the mid-term, soil C stocks generally recover to levels prior to afforestation [62].

2.2.4. Energy for Heating Farmhouses

To evaluate the number of farmhouses that could be heated with energy derived from poplar woody biomass, we need to know the biomass feedstock required to heat a single average-sized house over 9 years. Based on data from the *Canada Mortgage and Housing Corporation* [63], the energy required to heat an average-sized detached house (186 m^2 or 2000 square feet) for southern Québec has been estimated at 110 GJ/year for old houses (built before 1990) and at 80 GJ/year for new houses (built after 1990). The energy content of hybrid poplar on an oven-dry biomass basis (GJ/t) was adjusted by the average moisture content of biomass prior to combustion. As suggested by McKenny *et al.* [64], we have used Kenney's Lower Heating Value (LHV) equation [65] to adjust the higher heating value (HHV) of hybrid poplar wood for energy losses due to moisture removal:

$$\mathrm{LHV} = \mathrm{HHV} - (0.2205 \times h - (2.45 \times MC)/(1 - MC)) \tag{2}$$

where h represents the hydrogen content and MC the moisture content in the wood prior to combustion. Based on the review of Sannigrahi *et al.* [66], we assumed that the HHV of hybrid poplar wood is 19.38 GJ/t, while its hydrogen content is 5.7%. We also assumed that moisture content of hybrid poplar wood prior to combustion is 20%, which is the upper limit of moisture content recommended for log burning in wood stoves or furnaces [67]. Based on these assumptions, hybrid poplar LHV was estimated at 16.79 GJ/t of dry biomass.

Different types of heating systems exist for wood log burning and their energetic efficiency varies highly (Table 3). As no data is available about the relative proportion of those different heating systems across farmhouses of southern Québec, we used the mean efficiency value estimated in Table 3 (60.6%). The dry biomass required to heat one average-sized house in southern Québec during a single year was calculated as follows:

$$\begin{gathered}\text{Biomass} = \text{Heating energy requirement}/(\text{Biomass LHV} \times \text{Heating system efficiency}) \\ \text{For new houses}: (80\,\text{GJ/house/year})/(16.79\,\text{GJ/t} \times 0.606) = 7.86\,\text{t/house/year} \\ \text{For old houses}: (110\,\text{GJ/house/year})/(16.79\,\text{GJ/t} \times 0.606) = 10.81\,\text{t/house/year}\end{gathered} \tag{3}$$

Therefore, the usable energy in hybrid poplar biomass is approximately 10.18 GJ/t. Based on these calculations, a single new detached house would require about 70.7 tons of dry biomass over a 9-year period to satisfy its energy needs for heating, while an old detached house of the same size would require 97.3 tons. For the biomass supply of residential heating systems, only stem wood from hybrid poplar buffers was considered (no branch biomass), as farmhouse owners would likely harvest and burn wood logs and not wood chips. This is because around 90% of woodlot owners in southern Québec harvest wood strictly manually with the use of a chain-saw [68], suggesting that very few of these owners have the equipment required to produce wood chips following a whole-tree harvest.

Table 3. Efficiency of different common types of residential heating systems that use wood logs as a feedstock [63,69]. Advanced furnaces/boilers and advanced stoves refers to appliances certified as low-emissions by the EPA or according to the CSA B415.1 standards.

Wood Heating System	Lower Efficiency (%)	Upper Efficiency (%)	Mean Efficiency (%)
Furnaces/boilers	45	55	50
Advanced furnaces/boilers	55	65	60
Conventional stoves	50	65	57.5
Advanced stoves	65	85	75
All systems			60.6

Because heating system efficiency and LHV are proportionally related to the hybrid poplar biomass requirement of an average-sized house (Equation (3)), a sensitivity analysis was conducted to determine how changes in those parameters could impact the number of farmhouses heated with a fixed quantity of poplar biomass. The sensitivity analysis was conducted for heating system efficiency values ranging from 40% to 90%. The upper efficiency value would be representative of less common appliances, such as masonry heaters, which have an efficiency of up to 90% [70], while the lower efficiency value (40%) would be representative of a poorly located conventional wood stove. LHV ranging 10–18 GJ/t have been selected because HHV of poplar species found in natural ecosystems and plantations range 13.50–19.38 GJ/t [66].

2.2.5. Energy for Heating Greenhouses and Potential for Fossil Fuel Displacement

Woody biomass can be an interesting energy source to displace fossil fuel in the greenhouse growers industry of southern Canada [64]. Based on data provided by the *Syndicat des producteurs en serre du Québec* [71], the dry woody biomass feedstock required to heat one hectare of greenhouse would be approximately 1295 t/year. In the province of Québec, most greenhouses use fuel oil for heating (R. Fortier, Industries Harnois, personal communication), with an average consumption estimated at 500,000 L/ha/year [71]. Consequently, over 9 years, a total of 11,655 tons of dry woody biomass would be required to heat one hectare of greenhouses, which could contribute to the displacement of 4.5 million litres of fuel oil. As wood chips derived from short-rotation woody crops is a desirable feedstock for biomass boiler heating systems in the greenhouse industry [64], a whole-tree (stems + branches) harvest scenario in poplar buffers is assumed. Such a harvest scenario would also maximise nutrient exportation from agricultural riparian zones because branch biomass is the second-most important N and P storage pool in hybrid poplar buffers during the dormant season [35].

2.2.6. Forest Conservation Opportunities

Producing fuelwood biomass (wood logs) in hybrid poplar buffers could reduce the need to harvest fuelwood in farm woodlots, which could indirectly create opportunities for forest conservation [38]. Because fuelwood harvest is the dominant form of production activity in private forests of the studied areas [72], such an opportunity for conservation could easily be implemented. In the Estrie region (Magog River and Eaton River watersheds), 88% of private forest owners harvest fuelwood, compared to 81% in the Montérégie region (Pike River watershed) [68]. Consequently, to determine potential woodlot area that could be set aside for conservation following the replacement of forest derived fuelwood by hybrid poplar fuelwood produced in riparian buffers, we need to quantify the fuelwood biomass productivity of privately owned natural forests in the studied watersheds, and compare it to hybrid poplar buffer productivity. The forest biomass productivity was only calculated for merchantable stem wood biomass (10 cm diameter at the small end), because tree tops and branches are assumed to remain non-harvested given the growing uncertainty related to forest residue harvesting and the future sustainability of site fertility in natural ecosystems [73]. As already mentioned, landowners would mainly use a chain-saw to harvest fuelwood in their woodlot or riparian buffer, limiting their capacity to use branch biomass as a bioenergy feedstock.

In the Montérégie region, which contains the Pike River watershed, the mean annual productivity (merchantable wood only) of privately owned forests has been recently estimated at 2.86 m^3/ha/year [74], while for the Estrie region (Magog River and Eaton River watersheds), the mean productivity of privately owned forests has been estimated at 3.20 m^3/ha/year [75].

For proper comparisons between poplar buffer fuelwood productivity and natural forest fuelwood productivity, we needed to convert data from natural forest productivity to a dry biomass basis, because hybrid poplar wood has a much lower specific gravity than most native tree species found in southern Québec [76,77], but similar energy content per mass unit compared to other woody species [66]. To make such a stem volume to stem biomass conversion, we calculated a volume to biomass conversion factor, using a weighted arithmetic mean of specific gravity, which was based on specific gravity of the different species (or species group) [77] and their relative abundance in terms of standing volume obtained from regional forest inventory data [74,75]. Details of calculations are presented in the Supplementary Files (Table S1) and volume to biomass conversion factors, in terms of mean specific gravity, are presented in Table 4. In this study, the term "specific gravity" refers to the green specific gravity, based on the botanical standard of the oven-dry weight of the stem divided by its green volume (stem volume of a freshly cut tree) [78].

Table 4. Productivity, in terms of allowable cut (m^3/ha/year), of natural privately owned forest in the study area and for the three studied watersheds [74,75], and its conversion into stem wood biomass productivity (t/ha/year). The assumed stem wood biomass productivity of hybrid poplar buffers is also indicated (based on data from Fortier *et al.* [42]).

Region	Watershed	Forest Volume Yield (m^3/ha/year)	Mean Green Specific Gravity (t/m^3)	Natural Forest Stem Wood Biomass Yield (t/ha/year)	Hybrid Poplar Stem Wood Biomass Yield (t/ha/year)
Estrie	Magog River	3.20	0.45	1.44	4.2
	Eaton River	3.20	0.45	1.44	9.8
Montérégie	Pike River	2.86	0.48	1.37	15.8

2.3. Riparian Agroforestry Scenarios

We examined three riparian agroforestry scenarios related to the replacement of herbaceous buffers by multi-clonal hybrid poplar buffers along (1) 100%; (2) 25%; and (3) 10% of stream length located in agricultural areas of the studied watersheds. The 100% scenario provides an estimate of the full potential of poplar riparian agroforestry to provide ecosystem services at the watershed scale, while the two other scenarios represent more probable levels of adoption of a best management practice by farm owners (10% for low adoption; 25% for moderate adoption). An overview of the different assumptions made for ecosystem services calculation is provided in Table 5.

Table 5. Overview of assumptions made for the extrapolation of ecosystem services provided by hybrid poplar buffers at the watershed scale.

Parameters and Conditions	Assumptions
General	
Vegetation cover in non-forested agricultural riparian buffers	Non-managed herbaceous vegetation
Available land for tree buffer establishment	Along all non-forested perennial and intermittent stream sections located in agricultural areas
Time frame	9 years after hybrid poplar buffer establishment

Table 5. *Cont.*

Parameters and Conditions	**Assumptions**
Riparian agroforestry system implemented	
Multi-clonal hybrid poplar buffer	3 poplar clones with different parentages (D × N, DN × M, M × B)
Buffer width	4.5 m on each streambank (3 three rows wide, 1.5 m spacing between rows)
Tree density	2222 stems/ha
Rotation length	9 years
Harvest type	Clear-cutting
Wood and biomass production	
Hybrid poplar productivity in riparian buffers	Remains constant across each watershed, but varies between watersheds
Whole tree biomass yield (stems + branches)	5.7–21.4 t/ha/year (depending on the watershed)
Stem wood biomass yield	4.2–15.8 t/ha/year (depending on the watershed)
C, N and P storage	
Biomass C, N and P storage	C, N and P stocks in all biomass components of poplar buffers minus C, N and P stocks in all biomass components of non-managed herbaceous buffers
Soil C storage	No change related to poplar buffer establishment
Energy for heating farmhouses	
Average size of houses	186 m^2 (2000 ft^2)
Heating energy requirements	110 GJ/house/year for houses built before 1990 (Old houses) 80 GJ/house/year for houses built after 1990 (New houses)
Heating system efficiency	60.6%
Type of biomass	Hybrid poplar wood logs (stem biomass only)
Hybrid poplar lower heating value	16.79 GJ/t
Moisture content of poplar wood	20%
Energy for heating greenhouses and fossil fuel displacement	
Biomass requirement for heating GH	1295 t/ha/year (dry)
Type of biomass	Wood chips from hybrid poplar (stem + branch biomass)
Fuel oil requirements	500 000 l/ha of GH/year
Forest conservation opportunities	
Type of biomass harvested in farm woodlots	Stem wood (wood logs)
Stem wood biomass yield of natural private forestland	1.37-1.44 t/ha/year (depending on the watershed)
Characteristics of biomass harvested in farm woodlots	Same energy and moisture content as hybrid poplar biomass

3. Results and Discussion

3.1. Potential for Hybrid Poplar Riparian Buffers to Provide Ecosystem Services at the Watershed Scale

For the three studied watersheds, the potential for ecosystem service provision varies greatly for each km of stream where hybrid poplar buffers could replace non-managed herbaceous buffers (Table 6). This trend is related to the assumed difference in agricultural riparian zone fertility (productivity) that likely exists between the three watersheds. For each stream km where poplar buffers would be implemented, greater ecosystem service provision potential is expected in the Pike River watershed, where annual row crops are the dominant form of agriculture (Table 1), followed by the Eaton River and Magog River watersheds, where perennial crops and pasture are the dominant forms of agriculture (Table 4).

While ecosystem services per stream km are expected to be higher in the Pike River watershed (Table 6), this watershed has also the greatest proportion and length of streams bordered by agricultural land use, with 439 km of streams, representing 56% of total stream length for the entire watershed (Table 2). This situation strongly contrasts with the Magog River and Eaton River watersheds, where 115 km and 183 km of streams are bordered by agricultural land use, which respectively represent 14% and 17% of total stream length in these watersheds. Consequently, despite its smaller size in terms of watershed area (Table 1), there is a much greater ecosystem service provision potential in the Pike River watershed nine years following the replacement of herbaceous buffers by hybrid poplar buffers (Table 7).

Table 6. Potential ecosystem service provision after 9 years following the replacement of non-managed herbaceous buffers by hybrid poplar buffers along 1 km of stream in three watersheds with contrasted soil fertility. The biomass produced along streams could be used to heat farmhouses instead of fuelwood harvested in natural woodlots, allowing an opportunity for conservation. Alternatively, poplar biomass could be used to heat greenhouses and contribute to displace fossil fuel use.

Watershed (Paired Site/Fertility Class) [1]	Buffer Area (ha/km)	Wood Volume (m^3/km) [2]	Biomass (t/km) [2]		Biomass Storage Increase			Home Heating (Houses/km) [3,4]		Greenhouse [3,4]		Forest Conservation (ha/km)
			Woody	Stem	C (t/km)	N (t/km)	P (t/km)	New	Old	Heating (ha/km)	Fuel Oil Displaced (L/km)	
Magog River (Magog/low)	0.9	104	46	34	26.1	0.26	0.03	0.48	0.35	0.004	17,795	2.6
Eaton River (St-Isidore/moderate)	0.9	249	108	80	56.6	0.57	0.05	1.12	0.82	0.009	41,600	6.1
Pike River (Brompton/high)	0.9	405	173	128	96.0	1.01	0.13	1.81	1.31	0.015	66,985	10.4

[1] For paired site descriptions and data see Fortier *et al.* [35,42]; [2] Wood volume and biomass production services are mutually exclusive; [3] Heating energy for houses and heating energy for greenhouses are mutually exclusive; [4] The number of farmhouses or the area of greenhouses heated have been calculated based on the heating energy requirement over a total of 9 years (see Sections 2.2.4 and 2.2.5).

Table 7. Potential ecosystem service provision after 9 years following the replacement of 100%, 25% or 10% of non-managed herbaceous buffers by hybrid poplar buffers along perennial and intermittent streams of the three studied watersheds.

Buffer Scenarios	Watershed and Stream Type	Stream Length (km)	Buffer Area (ha)	Wood Volume (m^3)	Woody Biomass (t)		Biomass Storage Increase			Houses Heated [1]		Greenhouses [1]		Forest Conservation (ha)
					Whole Tree	Stem Wood	C (t)	N (t)	P(t)	New	Old	Heat Energy (ha GH)	Fuel Oil Displaced (L)	
100%	*Perennial*													
	Magog River	50	45	5221	2312	1702	1307	13	1.3	24	18	0.20	892,761	131
	Eaton River	64	58	15,998	6923	5112	3636	36	3.0	72	53	0.59	2,672,804	394
	Pike River	103	93	41,720	17,890	13,188	9898	104	13.1	186	136	1.54	6,907,519	1070
	Intermittent													
	Magog River	64	58	6701	2968	2185	1677	16	1.7	31	22	0.25	1,145,802	169
	Eaton River	118	106	29,453	12,745	9411	6694	67	5.5	133	97	1.09	4,920,871	726
	Pike River	336	302	135,862	58,260	42,947	32,233	338	42.5	607	442	5.00	22,494,317	3483
	All streams													
	Magog River	115	103	11,921	5280	3887	2984	29	3.0	55	40	0.45	2,038,563	300
	Eaton River	183	164	45 ,451	19,668	14,523	10,330	103	8.6	205	149	1.69	7,593,675	1121
	Pike River	439	395	177,582	76,151	56,135	42,132	442	55.6	794	577	6.53	29,401,836	4553

Table 7. *Cont.*

Buffer Scenarios	Watershed and Stream Type	Stream Length (km)	Buffer Area (ha)	Wood Volume (m^3)	Woody Biomass (t)		Biomass Storage Increase			Houses Heated [1]		Greenhouses [1]		Forest Conservation (ha)
					Whole Tree	Stem Wood	C (t)	N (t)	P(t)	New	Old	Heat Energy (ha GH)	Fuel Oil Displaced (L)	
25%	*Perennial*													
	Magog River	13	11.3	1305	578	426	327	3.2	0.3	6	4	0.05	223,190	33
	Eaton River	16	14.5	3999	1731	1278	909	9.1	0.8	18	13	0.15	668,201	99
	Pike River	26	23.2	10,430	4473	3297	2475	26.0	3.3	47	34	0.38	1,726,880	267
	Intermittent													
	Magog River	16	14.5	1675	742	546	419	4.1	0.4	8	6	0.06	286,450	42
	Eaton River	30	26.6	7363	3186	2353	1674	16.7	1.4	33	24	0.27	1,230,218	182
	Pike River	84	75.6	33,965	14565	10,737	8058	84.6	10.6	152	110	1.25	5,623,579	871
	All streams													
	Magog River	29	25.8	2980	1320	972	746	7	0.8	14	10	0.11	509,641	75
	Eaton River	46	41.1	11,363	4917	3631	2582	26	2.1	51	37	0.42	1,898,419	280
	Pike River	110	98.8	44,395	19,038	14,034	10,533	111	13.9	198	144	1.63	7,350,459	1138
10%	*Perennial*													
	Magog River	5	4.5	522	231	170	131	1.3	0.13	2.4	1.8	0.02	89,276	13
	Eaton River	6	5.8	1600	692	511	364	3.6	0.30	7.2	5.3	0.06	267,280	39
	Pike River	10	9.3	4172	1789	1319	990	10.4	1.31	18.6	13.6	0.15	690,752	107
	Intermittent													
	Magog River	6	5.8	670	297	218	168	1.6	0.17	3.1	2.2	0.03	114,580	17
	Eaton River	12	10.6	2945	1275	941	669	6.7	0.55	13.3	9.7	0.11	492,087	73
	Pike River	34	30.2	13,586	5826	4295	3223	33.8	4.25	60.7	44.2	0.50	2,249,432	348
	All streams													
	Magog River	11	10.3	1192	528	389	298	2.9	0.30	5.5	4.0	0.05	203,856	30
	Eaton River	18	16.4	4545	1967	1452	1033	10.3	0.86	20.5	14.9	0.17	759,368	112
	Pike River	44	39.5	17,758	7615	5613	4213	44.2	5.56	79.4	57.7	0.65	2,940,184	455

[1] The number of farmhouses or the area of greenhouses heated have been calculated based on the heating energy requirement over a total of 9 years (see Sections 2.2.4 and 2.2.5).

Over nine years, replacing all herbaceous buffers by hybrid poplar buffers along both perennial and intermittent streams (100% replacement scenario) would increase timber (or woody biomass) production by 11,921 m^3 (3887–5280 t), 45,541 m^3 (14,523–19,668 t) and 177,582 m^3 (56,135–76,151 t) in the Magog River, Eaton River and Pike River watersheds respectively (Table 7). Because replacing non-managed herbaceous buffers by hybrid poplar buffers leads to significant gains in C, N and P storage in vegetation biomass [35], increases in C and nutrient storage potential could reach 2984 t C, 29 t N and 3.0 t P in the Magog River watershed, 10,330 t C, 103 t N and 8.6 t P in the Eaton River watershed, and up to 42,132 t C, 442 t N and 55.6 t P in the Pike River Watershed, under the 100% replacement scenario (Table 7). This increase in C storage in the Pike River watershed over nine years (42,132 t C) is approximately equivalent to the gas emissions of 32,500 average-sized passenger vehicles during one year (each travelling 18,000 km/year) [79]. In the Pike River watershed, P losses from agricultural land have been estimated at 0.39 kg/ha/year for hayfields and pastures, and at 2.48 kg/ha/year for corn (*Zea mays*) fields (or 3.51 kg/ha and 22.3 kg/ha over nine years) [80]. Thus, an increase in biomass P storage of 55.6 t associated to poplar buffer implementation would be equivalent to P losses from 15,800 ha of hayfield or pasture, or from 2500 ha of cornfields over 9 years. Nitrogen losses from agricultural land have been established at 27 kg N/ha/year or 243 kg N/ha over 9 years in the nearby Beaurivage watershed (40% annual row crops, 60% pasture/hayfield) in southern Québec [81]. Based on these values, increasing N storage by 442 t N with poplar buffers in the Pike River watershed would be equivalent to the N losses from 1800 ha of cultivated land over nine years.

The large-scale implementation of tree riparian buffers would be an excellent contribution to improving water quality and to rehabilitating stream habitats in southern Québec. All watersheds from this region have a high to very high conservation priority because they support diverse fish communities and very productive aquatic ecosystems, while being threatened by high levels of anthropogenic stressors [82]. Environmental problems related to cyanobacterial blooms are of special concern in the Pike River watershed and in its receiving water body, the Missisquoi Bay of Lake Champlain. Phosphorus enrichment in this bay is a major factor contributing to cyanobacteria proliferation; a factor mostly related to agricultural activities in the watershed [83]. More than a decade ago, cyanobacterial blooms and elevated cyanotoxin concentrations in the water led to public health warnings for swimming and for fish and water consumption from the lake, resulting in beach closings, but also in the desertion of local campgrounds and commercial sites [84]. In summer 2015, cyanobacterial blooms in Missisquoi Bay still made the headlines of national news [85], suggesting that issues of water pollution by excess nutrient inputs from cultivated land have not yet been resolved.

However, increasing nutrient storage in the vegetation biomass of poplar buffers may only have a partial effect on P exports from the Pike River watershed, as 82% of annual P discharges occur outside of the growing season, during spring snowmelt and spring or autumn rainfall events on bare agricultural soils [83]. For agricultural non-point source pollution control, additional best management practices should be used to complement riparian buffer establishment. These could include building up soil health (no tillage or reduced tillage, crop rotation), in-field water control (upland filter strips, controlled drainage), and below-field water control (constructed wetlands) [86]. A strategy which aims at establishing efficient riparian buffers for water quality protection should also consider variable width buffers and priority areas for placement, based on adjacent farmland cropping system, slope, soil type, pollutant to be trapped/transformed, and hydrological connectivity (concentrated flow path) between fields and streams [87–89] (Figure 2). Although fixed-width buffers are administratively simpler to manage [90], they may have limited non-point source pollution control capacity in agricultural landscapes with non-uniform topographical features and/or cropping systems. To assist land planners in the establishment of more efficient water quality buffers on farmland with non-uniform runoff patterns, a GIS-based tool using a digital elevation model has recently been developed (the *AgBufferBuilder*) [91].

Establishing buffers on smaller (low order) and intermittent streams is very important, as headwater streams comprise more than 85% of the total length of stream networks, thus collecting most of the water and dissolved nutrients from adjacent terrestrial ecosystems [92]. In all studied watersheds, intermittent farm streams without a forest cover accounted for more stream length than perennial farm streams without a forest cover (Table 2), suggesting that these intermittent streams are major recipients of nutrient, pesticide and sediment pollution. Although not considered in this study, it would be very useful to map ephemeral streams, road side ditches, swales and surface field drainage ditches in agricultural watersheds, as they are key hydrological features that should also be considered for riparian buffer establishment [93].

Figure 2. Examples of concentrated flow paths in hybrid poplar buffers established along a crop field (**left**) and along a pasture (**right**) riparian zone in southern Québec. In these hot spots for sediment and nutrient transport, wider buffers and additional conservation practices (ex: stiff-stemmed filter strip, ephemeral stream fencing) would be needed to allow surface runoff dispersion/infiltration and improve the water quality function [20].

From an energetic perspective, the use of riparian buffers to produce biomass for bioenergy could be a significant contribution to the energyscape (*sensu* Howard *et al.* [94]) of southern Québec. Planting hybrid poplars along the 439 km of farm streams in the Pike River watershed could provide 76,151 tons of whole-tree biomass (stems + branches) in less than a decade (Table 7). This biomass could be chipped and used to heat 6.5 ha of greenhouses during nine years, which could displace 29.4 million litres of non-renewable fuel oil. Alternatively, the stem wood biomass produced (56,135 t) could be transformed into fuelwood that could be used locally to heat between 577 and 794 average-sized farmhouses for nine years (Table 7).

A major indirect contribution to forest conservation at the watershed scale could also be achieved if fuelwood production in poplar buffers could replace fuelwood harvested in farm woodlots [38]. This is because the stem wood biomass productivity of poplar buffers is about 3 to 12 times greater than natural forest productivity in the studied watersheds (Table 4). Such differences in biomass productivity between upland forests and poplar riparian buffers are most likely related to greater availability of resources in linear agricultural riparian buffers (high nutrient, water and light availability), and the particularly high resource uptake rate and growth rate of hybrid poplars compared to native forest tree species [39,95]. Consequently, producing poplar fuelwood along 439 km of streams in the Pike River watershed, which represents a poplar buffer area of 395 ha, would be enough to compensate the fuelwood production loss associated with the conservation of 4553 ha of farm woodlots (Table 7). This indirect potential contribution to forest conservation would be significant, as approximately 20,000 ha of forests are found in the Pike River watershed [51]. Furthermore, a watershed scale implementation of poplar riparian buffers would rapidly increase forest connectivity at the landscape level, especially in the north-eastern part of the Pike River watershed, where many isolated forest fragments of various sizes are interconnected along the hydrological network (Figure 1). Many of these forest fragments could be simply reconnected together by establishing tree corridors along both intermittent and perennial streams. Additionally, positive effects of poplar buffers on terrestrial biodiversity will likely be greater in the Pike River watershed because it has the lowest forest cover and the highest proportion of intensive agricultural land use (Figure 1, Table 1). This is because local allocation of habitat is far more important in oversimplified landscapes dominated by intensive agriculture than in more complex landscapes with a higher proportion of forest cover [96]. Lastly, the indirect forest conservation opportunities created by large scale poplar buffer plantings would also create indirect C storage opportunities, as protected forests would have the chance to grow older, a process strongly linked with soil and biomass C accumulation in forest ecosystems [97,98].

At a projected width of 4.5 m (3 poplar rows), poplar riparian buffers cannot provide an optimal level of ecosystem services, and certainly not natural conditions typical of undisturbed riparian zones. Much wider riparian buffers will be needed to provide an optimal level of ecosystem services [6,9,11,16,99]. However, wide buffers may be hard to implement watershed-wide, especially where intensive agriculture dominates, as a major disservice of tree buffer establishment is the loss of agricultural land. In the province of Québec, the current legislation allows land cultivation or livestock pasturing near streams, providing that a narrow vegetation buffer of 3 m be maintained [100]. Consequently, increasing buffer width at 4.5 m, would require that a 1.5 m wide strip of agricultural land be converted into tree buffers along farm streams. In terms of area, planting 4.5 m wide poplar buffers along all non-forested farm streams would lead to an agricultural land loss of 34 ha in the Magog River watershed, of 55 ha in the Eaton River watershed, and of 132 ha in the Pike River watershed, representing between 0.5 and 1.1 % of total cultivated land depending on the watershed (Table 8). Due to the very high agricultural land value in the Pike River watershed ($22,624/ha in 2014) [101], the land value of 132 ha of agricultural land is approximately $3 million (Table 8). In this same watershed, increasing buffer width to 10 m, as recommended by the provincial *Politique de protection des rives, du littoral et des plaines inondables* [100], would lead to an agricultural land loss of 615 ha, representing a value of nearly $14 million. As recently reviewed by Sweeney and Newbold [11], forest buffers of 30 m or wider would be needed to maintain natural conditions in terms of water quality, habitat, and biotic features along the stream network. Extending buffer width to 30 m in the Pike river watershed would lead to a loss of 2370 ha of agricultural land, representing a value of more than $53 million (Table 6). Such levels of land use conversion would seriously impinge on the food production service and would likely be socially unacceptable among the farming communities [102]. In this context, landowners that implement wide riparian buffers should receive direct financial compensation for the loss of cultivated land, as many ecosystem services provided by riparian buffers have no market value for the moment. Presently, subsidies covering 70%–90% of buffer establishment costs are available [103], but no compensation program for agricultural land loss exists for Québec farmers.

Table 8. Potential loss of cultivated land following the implementation of hybrid poplar buffers of various width along all non-forested perennial and intermittent farm streams in the three studied watersheds. The value of the cultivated land that would be lost is also indicated (in Canadian $).

Buffer Width	Watershed and Stream Type	Stream Length (km)	Poplar Buffer Area (ha)	Legal Buffer Area (ha) [1]	Loss of Cultivated Land (ha)	Total Cultivated Land (ha)	Cultivated Land Lost (%)	Agricultural Land Value ($/ha)	Agricultural Land Value ($)
4.5 m	*Perennial streams*								
	Magog River	50	45	30	15	3114	0.48	4040	60,806
	Eaton River	64	58	39	19	8551	0.23	4040	77,871
	Pike River	103	93	62	31	26,133	0.12	22,624	699,896
	Intermittent streams								
	Magog River	64	58	39	19	3114	0.62	4040	78,041
	Eaton River	118	106	71	35	8551	0.42	4040	143,367
	Pike River	336	302	201	101	26,133	0.39	22,624	2,279,210
	All streams								
	Magog River	115	103	69	34	3114	1.10	4040	138,847
	Eaton River	183	164	110	55	8551	0.64	4040	221,238
	Pike River	439	395	263	132	26,133	0.50	22,624	2,979,106
10 m	*Perennial streams*								
	Magog River	50	100	30	70	3114	2.26	4040	283,762
	Eaton River	64	129	39	90	8551	1.05	4040	363,398
	Pike River	103	206	62	144	26,133	0.55	22,624	3,266,182
	Intermittent streams								
	Magog River	64	129	39	90	3114	2.89	4040	364,190
	Eaton River	118	237	71	166	8551	1.94	4040	669,048
	Pike River	336	672	201	470	26,133	1.80	22,624	10,636,312
	All streams								
	Magog River	115	229	69	160	3114	5.15	4040	647,951
	Eaton River	183	365	110	256	8551	2.99	4040	1,032,446
	Pike River	439	878	263	615	26,133	2.35	22,624	13,902,493
30 m	*Perennial streams*								
	Magog River	50	301	30	271	3114	8.70	4040	1,094,509
	Eaton River	64	386	39	347	8551	4.06	4040	1,401,678
	Pike River	103	619	62	557	26,133	2.13	22,624	12,598,129
	Intermittent streams								
	Magog River	64	386	39	348	3114	11.16	4040	1,404,732
	Eaton River	118	710	71	639	8551	7.47	4040	2,580,615
	Pike River	336	2015	201	1813	26,133	6.94	22,624	41,025,773
	All streams								
	Magog River	115	687	69	619	3114	19.86	4040	2,499,241
	Eaton River	183	1095	110	986	8551	11.53	4040	3,982,293
	Pike River	439	2634	263	2370	26,133	9.07	22,624	53,623,903

[1] The legal buffer area refers to the buffer area calculated using 3 m wide buffers along streams, which is the norm according to the current legislation on agricultural land in the Province of Québec [100].

The methodology used for extrapolating ecosystem services suggests that fertility variations between watersheds result in a large variation of hybrid poplar yield (per km of stream), further resulting in proportional variations in the heating energy produced, in potential for fossil fuel displacement or in forest area that could be set aside for conservation (Table 6). Such variations in watershed productivity would also greatly affect the C and nutrient storage services of poplar buffers after nine years. These assumptions related to variations in ecosystem services across a regional gradient of fertility are supported by recent studies done in southern Québec [35,42,104,105]. Therefore, used as a sole predictor variable, the length of the stream network available for hybrid polar buffer implementation may not be a robust indicator of the ecosystem services provision potential abovementioned, unless site quality remains relatively constant across sites or watersheds. This highlights the need to collect data on biomass productivity and C and nutrient stocks across multiple riparian buffer sites in each of the studied watersheds in order to improve the robustness of projections about ecosystem service provision at the watershed scale.

In addition, our projections related to the creation of indirect forest conservation opportunities resulting from the replacement of fuelwood harvested in woodlots by hybrid poplar fuelwood harvested in riparian buffers contain a certain amount of uncertainty. We possibly underestimated such a service because the only available data on private forest productivity in the Estrie region (Magog and Eaton River watersheds) seems quite optimistic (3.2 m^3/ha/year) [75], compared to forest productivity estimates on public forestland in the study area (1.5 m^3/ha/year in the Estrie region and at 1.6 m^3/ha/year in the Chaudière-Appalaches region) [106].

Improving the design of riparian buffers could also result in greater ecosystem service provision per kilometer of stream planted with hybrid poplars. For example, as several services are directly and positively affected by biomass yield (Tables 6 and 7), the selection of the most productive hybrid poplar genotypes could be a way to maximise productivity-related services [41,42]. However, this would require a good knowledge of the suitability of different genotypes across changing site conditions given the frequent Genotype × Environment interactions observed in hybrid poplar yield at the regional scale [104,107]. Otherwise, the use of generalist genotypes (*P. maximowiczii* hybrids) could be a way to obtain good yields in variety of environments, including colder (higher elevation) sites [105,107,108].

Improving the efficiency of residential heating systems could also be a way to achieve a higher amount of ecosystem services because energetic efficiency is proportionally related to the biomass requirement of a single farmhouse (Table 9). Thus, the number of houses that could be heated with a fixed biomass quantity is very sensitive to changes in heating system efficiency (Table 9). For example, under the 100% buffer scenario, the Pike river watershed could produce 56,135 t of wood logs (Table 7), a biomass supply that could heat 381–524 houses equipped with a low efficiency (40%) woodstove or 857–1178 houses equipped with a very efficient (90%) masonry heater (Table 9). Such a change in heating system efficiency (from 40% to 90%) would reduce the need to extract biomass from poplar buffers by 56% across the whole watershed, creating the opportunity to manage poplar buffers more extensively (see Section 3.2), with the goal of enhancing services related to canopy closure (stream temperature regulation, habitat or corridor for native forest and stream biodiversity, natural disturbance protection, *etc.*). In other words, more multifunctional hybrid poplar buffers could be implemented if energetic needs would be lower for individual farmhouses. However, the replacement of low efficiency appliances by very efficient heating systems can be relatively costly (up to 10,000$ for masonry heaters [109]), which may delay such technological change in the absence of adequate financial incentives.

There is also uncertainty regarding the estimated LHV of hybrid poplar wood in this study (16.79 GJ/t), which was calculated from hybrid poplar HHV (19.38 GJ/t) found in the literature, without any precision regarding genotype [66]. HHV may likely change for hybrid poplar clones of different parentages, as large variations in HHV have been reported for the different natural poplar species (16.26 GJ/t for *P. deltoides*, 15.00 GJ/t for *P. trichocarpa*, 13.50 GJ/t for *P. tremuloides*) [66]. Thus, the selection or development of poplar genotypes that have a high heating value per biomass unit should receive the same attention as selecting the most productive clones. An increase in LHV, alike a biomass yield increase, results in a proportional increase in the number of houses heated with the biomass supply produced in each watershed (Tables 6 and 9). Consequently, for the provision of bioenergy services many initiatives should be undertaken simultaneously, including the use of the most productive clones having high calorific values, an upgrade in heating system efficiency (replacement of old appliances) and a reduction in heating energy needs per unit of area in farmhouses and greenhouses.

In the study area, increase in mean annual temperature and in growing season length resulting from global warming [110] could also improve hybrid poplar yield and reduce the heating energy requirements in the greenhouse industry and the residential sector; a scenario that would create a positive synergy regarding the number of houses or the greenhouse area that could be heated with poplar biomass produced at the watershed scale. On the other hand, global warming may enhance the dispersal of new pests in the study area, while increasing the severity and/or frequency of natural disturbances [111,112]. This situation could increase mortality and negatively affect hybrid poplar productivity and its related services, as hybrid poplars are not very resilient tree species (low mechanical properties and high pest vulnerability) [113,114].

Finally, it may be argued that it would be technically difficult to establish hybrid poplar buffers, within a short timeframe, across an entire agricultural watershed in southern Québec. On the one hand, planting hybrid poplars along the 439 km of non-forested farm streams in the Pike River watershed would require 877,690 hybrid poplar bare root plants (395 ha of buffer × 2222 trees/ha), which is well below the yearly production capacity of the provincial nursery that provides hybrid poplar planting stocks in Québec [26]. On the other hand however, establishing buffers along 439 km of stream in the same year would be hard to achieve because such a large watershed-scale project would require the prompt participation of a large number of landowners. More realistically, 49 km of stream could be afforested each year for the 9 years to come. This would require planting approximately 97,500 trees/year, based on the riparian agroforestry system proposed in this study (see Section 2.2.1). A gradual implementation of poplar buffers over a nine year period would also create the opportunity to harvest only 1/9 of the total buffer area each year, which would create a mosaic of uneven aged poplar buffers at the watershed scale, while providing a more constant supply of biomass each year for heating farmhouses or greenhouses. Thus, in the Pike River watershed, the afforestation of 49 km of stream per year over nine years would start to generate the annual biomass feedstock required to heat 577–794 farmhouses or 6.5 ha of greenhouses (Table 7) only at the end of year 9, following the clear-cutting of hybrid poplars along 49 km of stream.

Table 9. Effect of the variation in heating system efficiency or lower heating value (LHV) of hybrid polar biomass on the usable energy content of biomass, on the biomass requirement per farmhouse and on the number of farmhouses that could be heated for each watershed after 9 years following the replacement of 100% of non-managed herbaceous buffers by hybrid poplar buffers along all streams (perennial + intermittent).

LHV	Heating System Efficiency (%)	Usable Energy (GJ/t)	Biomass (t/house)		Number of Houses Heated per Watershed [1]					
					Magog River		Eaton River		Pike River	
			New	Old	New	Old	New	Old	New	Old
16.79	40	6.7	107.2	147.4	36	26	135	99	524	381
16.79	50	8.4	85.8	117.9	45	33	169	123	654	476
16.79	60	10.1	71.5	98.3	54	40	203	148	785	571
16.79	70	11.8	61.3	84.2	63	46	237	172	916	666
16.79	80	13.4	53.6	73.7	73	53	271	197	1047	762
16.79	90	15.1	47.7	65.5	82	59	305	222	1178	857
10.00	60.6	6.1	118.8	163.3	33	24	122	89	473	344
12.00	60.6	7.3	99.0	136.1	39	29	147	107	567	413
14.00	60.6	8.5	84.8	116.6	46	33	171	125	662	481
16.00	60.6	9.7	74.2	102.1	52	38	196	142	756	550
18.00	60.6	10.9	66.0	90.7	59	43	220	160	851	619

[1] The stem wood biomass supply is 3887 t for the Magog River watershed, 14,523 t for the Eaton River watershed and 56,135 t for the Pike River watershed (see Table 7).

3.2. Hybrid Poplar Buffers for Maximum Multiple Ecosystem Services and Fewest Disservices

Other ecosystem services than those quantified in the previous section may be provided if hybrid polar buffers are implemented at a watershed scale and those potential services should be considered altogether in the design of poplar buffers. One of the major challenges is how to design and manage such riparian buffers for the provision of multiple ecosystem services, while avoiding or mitigating potential disservices [21]. This section provides a holistic view of the different ecosystem services (including goods) that may be provided by poplar riparian buffers, while identifying potential trade-offs and management recommendations to optimise services and reduce disservices. Table 10, presented at the end of this section, integrates all of this information.

Concerning regulation services, the previous section has presented results of the potential of poplar buffers for stocking large amounts of nutrients (N and P) in biomass, a process closely linked to nutrient uptake by trees during the growing season. Reduction of more than 50% in the availability of soil nitrate (NO_3) and P during summer was observed in hybrid poplar buffers when compared to adjacent herbaceous buffers [35]. However, poplar buffers can also reduce non-point source nutrient pollution outside of the growing season, especially when the poplar rhizosphere can interact with groundwater. For example, groundwater NO_3 retention, during winter months, reaches almost 100% in the first 5 m of a poplar buffer (probably because of denitrification), an efficiency that was higher than that of an adjacent herbaceous buffer [44]. Such reduction in nutrient loads to streams would also increase stream C sequestration, as instream decomposition of terrestrial litter is co-limited by water N and P concentrations [115]. Therefore, creating a new terrestrial sink for atmospheric CO_2 and excess soil nutrients with poplar riparian agroforestry would also reduce C losses associated to instream organic matter mineralisation, which would have a cumulative positive effect on the global climate regulation service. Microbial activity in the poplar rhizosphere and pesticide uptake/transformation by poplars may also contribute to agrochemical pollution mitigation [116,117]. Additionally, rapid height growth of poplar buffers creates a physical barrier that can reduce aerial pesticide drift into streams and wetlands.

The development of key structural attributes also increases the strength of riparian vegetation/stream interactions. Such interactions improve regulation and habitat provision services in stream ecosystems. Even in narrow poplar buffers, canopy closure can be almost complete as early as six years along headwater streams (Figure 3a). Canopy closure improves stream shading, reduces periphyton blooms [118], maintains cooler water temperatures [48], and allows inputs of terrestrial invertebrate prey into streams [119]. Buffers with rapid canopy development would be particularly needed along small streams in open fields, as predicted increases in water temperatures resulting from global warming may exceed the thermal tolerances of some aquatic species [120].

Planting broadleaved trees along farm streams also enhances leaf litter inputs (Figure 3b), which can restore trophic relationships in aquatic ecosystems [121], while contributing to higher instream nutrient retention and C sequestration [11,122]. It should be highlighted that stream invertebrates select litter largely on the basis of its food quality, whether it is from exotic hybrid poplars or native species [123]. Hybrid poplar litter is known to be rapidly consumed by benthic stream invertebrates because it is N-rich and soft [123]. Thus, hybrid poplar leaf litter would locally enhance the detrital energy base of streams, even in streams with lower litter retention capacity [122,123]. Poplar roots growing directly into stream water can further provide energy to the stream food web, while contributing to instream C sequestration and nutrient uptake (Figure 3c). Additionally, increase of stream water and riparian zone soil temperatures resulting from riparian forest clearing have been linked to increasing fluxes of several greenhouses gas (N_2O, CH_4 and CO_2), [124]. Consequently, cooler temperatures provided locally following riparian tree canopy restoration would have high potential for greenhouse gas mitigation in riparian zones and in stream ecosystems.

The rapid development of large tree stems in streamside habitats is another important structural element of poplar buffers. Tree stems reduce flow velocity during flooding events and allow woody debris and sediment accumulation in the riparian zone (Figure 3d), thereby protecting infrastructures located downstream. Forest vegetation also provides much greater channel and bank stability, than herbaceous vegetation [11,125]. Although bank erosion is a desirable feature of natural stream ecosystems [126], too much bank erosion along channelized farm streams can reduce water quality and impair stream habitats [11], as bank erosion is a major contributor of suspended sediments and P [127]. Therefore, when replacing herbaceous vegetation, poplar buffers are expected to reinforce streambanks (Figure 3e), as they rapidly form deep and extensive root systems along degraded farm streams [43]. Rooting depths of more than 5 m have been reported in natural riparian poplar stands [128], while rooting depths exceeding 3 m have been reported in four-year-old hybrid poplar plantations [129]. In a context where the frequency and magnitude of storm flow events are exacerbated by agricultural land use and by global warming [130,131], streambank reinforcement with deep-rooted poplars could be important to prevent high rates of erosion. Such a streambank stabilisation strategy with poplar plantings was already used two millennia ago by native North Americans [27].

Another important structural attribute of poplar buffers, is that they can become a source of large deadwood for streams on a decanal timeframe (Figure 3f). As reviewed by Pollock and Beechie [132], the major role of riparian forests in enhancing stream biodiversity is to produce sufficient deadwood of different sizes to form complex wood jams, which further contribute to sediment trapping, water velocity reduction, pool formation, and complex stream or riparian habitat creation. While it may take several decades to form such complex wood jams following the regrowth of natural forests [4], planting hybrid poplar genotypes that have a forking stem habit and a low wood density could accelerate the production of large woody debris in riparian areas [42]. Individual trees that fall into the stream also contribute to pool formation, while providing cover for aquatic organisms [132], and additional substrate for instream microbial denitrification [133].

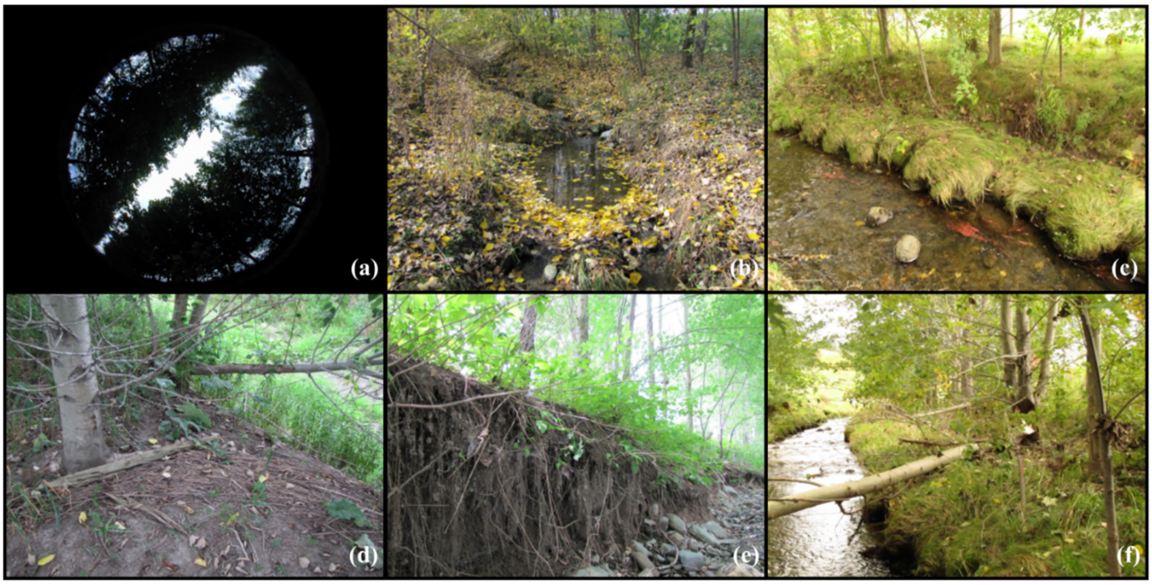


Figure 3. (**a**) Canopy closure shown by a hemispherical photo taken above a headwater farm stream protected by a 6 year-old poplar buffer (Brompton, QC, Canada); (**b**) leaf litter input to stream from a 9 year-old poplar buffer (St-Isidore-de-Clifton, QC, Canada); (**c**) instream poplar root development in a 12 year-old poplar buffer (Magog, QC, Canada); (**d**) woody flotsam interception and flood sediment deposition in a 9 year-old poplar buffer (Bedford, QC, Canada); (**e**) important colonisation of a streambank by tree roots in a 9 year-old poplar buffer (Brompton, QC, Canada); (**f**) large woody debris naturally fallen in the stream zone in a 12 year-old poplar buffer (clone MxB-915311, Magog, QC, Canada).

Poplar buffers also provide refuge for terrestrial and wetland biodiversity on farmland. Bird nests have been observed five years following hybrid poplar establishment along farm streams (Figure 4a). Additionally, the particular rooting habit of some poplar genotypes may serve as a structural element for burrow placement (Figure 4b). The soft wood of hybrid poplars is also very attractive to woodpeckers [31], which produce cavities that can provide further nesting and roosting habitat for other cavity-using species (mammals, birds, reptiles, amphibians and insects) [134]. One hybrid poplar genotype (clone DNxM-915508) appears to be particularly used for feeding by the yellow-bellied sapsucker (*Sphyrapicus varius*) (Figure 4c) [31]. Even pileated woodpeckers (*Dryocopus pileatus*), generally associated with interior habitat of mature forests [135], have been observed feeding on dead poplars of a five-year-old buffer that was isolated from the nearest forest patches (J. Fortier and B. Truax, field observations). Small mammals typical of forest habitats (*Napaeozapus insignis*, *Peromyscus maniculatus* and *Sorex cinereus*) have also been captured in a 9-year old poplar buffer that was connected to an adjacent forest habitat, which suggests that some forest species will use poplar buffers as corridors [31]. On the other hand, a crop damaging species typical of open habitats, the meadow vole (*Microtus pennsylvanicus*) [136], was captured in herbaceous buffers, but not in the poplar buffers [31]. Predators of crop damaging species, such as the short-tailed weasel (*Mustela erminea*) have equally found refuge in hybrid poplar buffers (Figure 4d). Although they usually have lower conservation value than natural forests, numerous studies confirm the role of planted poplars as a refuge for wildlife on farmland [137–141]. Moreover, pest control in cropping systems may be improved by the integration of linear poplar structures in agro-ecosystems because such structures can become reservoirs of beneficial insects (predators and parasitoids) [140]. By providing shade, wind protection and reduced herbaceous vegetation cover, poplar buffers can also provide a favourable environment for the restoration of more shade-tolerant native tree or herb species, which can be under-planted or regenerate naturally (Figure 4e,f) [29,30,142–144]. Additionally, rapid canopy closure in poplar buffers can reduce the abundance of shade-intolerant introduced (exotic) herbaceous species, which includes many agricultural weeds [30].

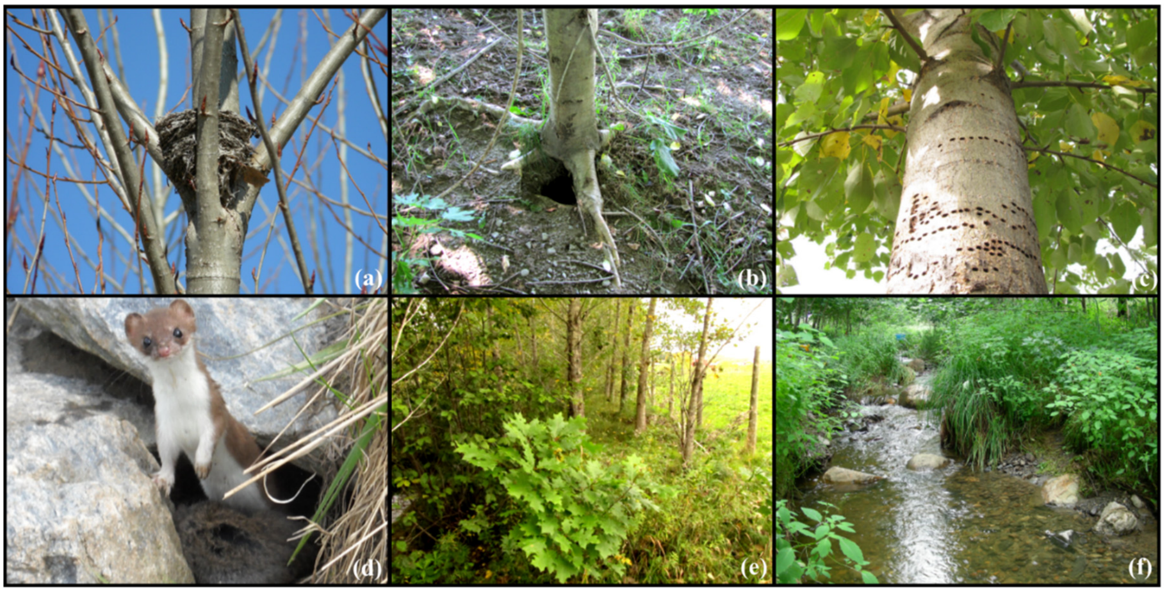


Figure 4. (**a**) A bird nest in a 5-year old hybrid poplar buffer (Brompton, QC, Canada); (**b**) a burrow in a 9-year old poplar buffer (clone MxB-915311, St-Isidore-de-Clifton, QC, Canada); (**c**) small cavities created by the yellow-bellied sapsucker (*Sphyrapicus varius*) to attract insects on which it feeds (clone DNxM-915508, Roxton Falls, QC, Canada); (**d**) use of a 9-year old hybrid poplar buffer for hunting and den making by a short-tailed shrew (*Mustela erminea*) (Magog, QC, Canada); (**e**) 5-year old red oak (*Quercus rubra*) planted on top of the streambank in a gap following a partial poplar harvest; (**f**) naturally established native wetland herbs (*Impatiens capensis* (in foreground) and several species of *Carex*) in a 6-year old hybrid poplar buffer (Brompton, QC, Canada).

Concerning production services, poplar buffers can be used to diversify farmland economy by providing biomass for bioenergy and biofuels [32–34,145], but also raw material for pulp and paper, lumber, veneer, plywood, composite panels, structural composites, containers, pallets, furniture components, match splints and chopsticks [76] (Figure 5a,b). Bioproducts from poplars (propolis, flavonoids, bud extracts) have also various applications in medicine, health foods, cosmetics and plant disease control [146,147]. Poplar foliage and rameal wood are currently used as an inexpensive fodder during drought or as supplements to increase livestock reproductive capacity [148,149]. Litter fall from poplar buffers reaching adjacent cropping systems can contribute to improving soil fertility and food crop productivity [150]. Planted poplars are also naturally colonised by a wide array of fungi, including the oyster mushroom (*Pleurotus ostreatus*), a well-known edible mushroom [151] (Figure 5c), which can also be cultivated on poplar logs.

Furthermore, a watershed scale implementation of poplar riparian buffers could provide some cultural services. The use of poplar buffers by different bird species could improve farmland value for bird watching, while the improvement of instream and riparian habitats following buffer implementation could be beneficial for game hunting and fishing. A major issue that remains is how well these novel riparian ecotones will be perceived among rural communities, as tree buffers may close up open landscapes and compete with traditional agricultural land use [152–154]. Still, poplar buffers composed of various genotypes that have different shades of yellow in their autumn foliage and different tree architectures could improve the aesthetic value of agricultural landscapes (Figure 5d–f), especially in areas where extensive crop monocultures currently dominate.

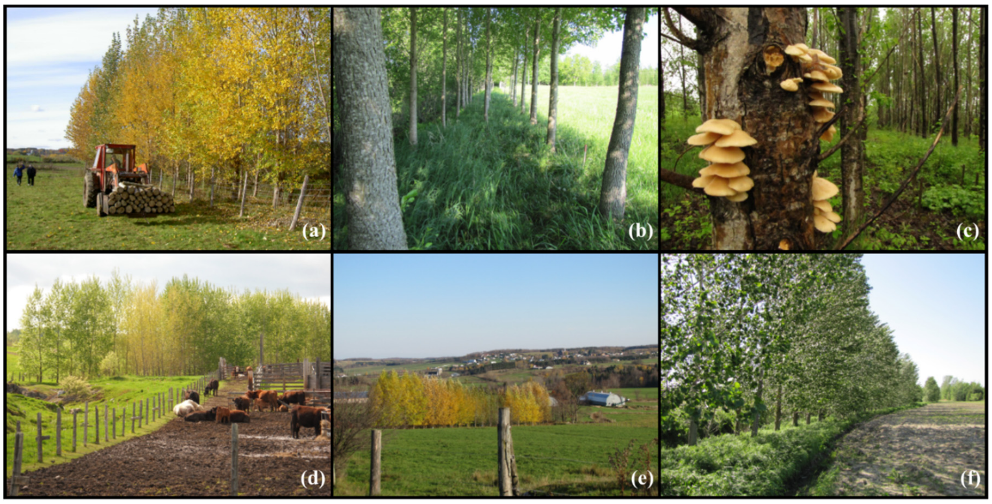


Figure 5. (**a**) Fuelwood (biomass) production following partial harvest in a 6-year old poplar buffer (Brompton, QC, Canada); (**b**) pruned hybrid poplar buffer for the production of solid wood products; (**c**) *Pleurotus ostreatus*, a native edible mushroom, naturally growing on a decaying hybrid poplar (Brompton, QC, Canada); (**d**–**f**) hybrid poplar buffers in various farmland settings.

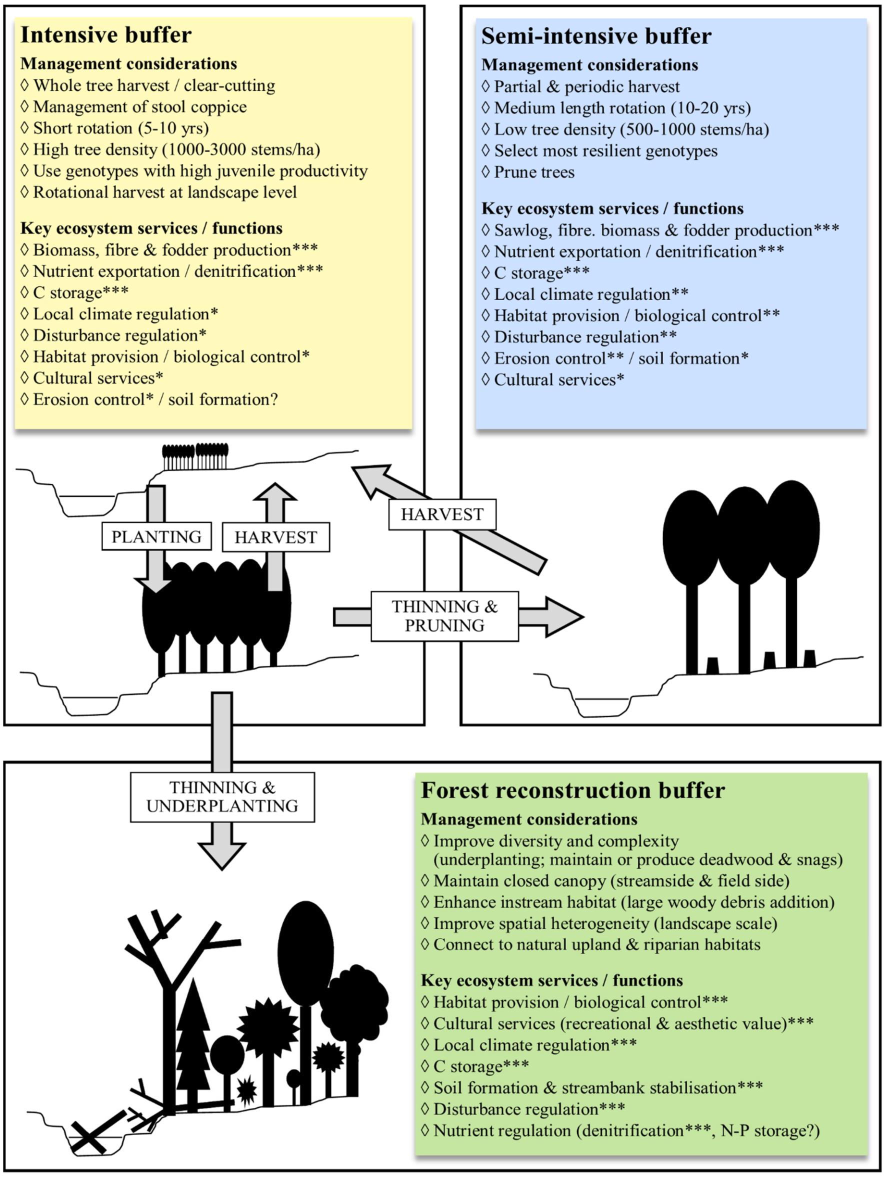
What could place additional limitations on ecosystem service provision by poplar buffers? First, it is widely assumed that buffer width is a major factor affecting regulation and habitat provision services [6,9,11,20,48,87,99]. The legal context related to riparian zone management can also be an obstacle for the production services that require tree harvesting, as some jurisdictions restrict such activities. In addition, many ecological, hydrological and biogeochemical functions/services provided by tree buffers depend on their level of spatial connectivity with adjacent stream ecosystems, with remnant natural riparian forests, with upland habitats, and with groundwater [155]. Thus, the restoration of some services will require particular spatial configurations or specific locations in watersheds (ex: habitat provision, corridor for dispersal of plants and animals, stream shading, flood control, groundwater purification), while some other services are independent of spatial configuration within landscapes (e.g., C storage, wood production) [21,156]. Therefore, for some services, the establishment of buffers across multiple boundaries will require a high level of cooperation between private landowners, which may complicate implementation [156].

In many agricultural areas, establishing tree buffers alone may not be sufficient to promote stream biodiversity. As argued by Parkyn *et al.* [48], proximity to a source of colonists and the presence of colonisation pathways may be of overriding importance to allow rehabilitation of stream organisms such as invertebrates. Additionally, many studies suggest that riparian zone quality, in terms of forest cover, is not a significant factor affecting stream biodiversity, with actual or past land use type across the whole watershed being the dominant factor [131,157–161]. Still, a 20 m wide hybrid poplar buffer (20 years old) established along 3.6 km of a 5 m wide farm stream, was found to positively affect stream habitat quality (reduction in stream water N and P, increased water clarity, temperature reduction), which lead to invertebrate community improvement [48].

However, in watersheds where agricultural development has increased hydrological connectivity between the land and streams, some level of hydrological restoration is a prerequisite to stream biodiversity enhancement [162]. In such a context, efforts should first be invested at retaining storm waters upland, in order to create more natural flow regimes [162]. Then, best management practices aiming at reducing contaminant load to streams should be used [162]. Once these issues are resolved, the improvement of stream structure can be undertaken, if necessary [162].

Given that poplars are among the beaver's (*Castor canadensis*) favorite foods, the presence of beavers in lowland streams is another factor that could seriously affect the structure and function of poplar buffers [163], especially in flood prone areas [164]. Equally, the presence of a subsurface drainage system may be a limitation for the planting of phreatophytic poplars, as their root systems may obstruct subsurface drains [43]. However, this potential disservice has not been adequately studied and its relative importance is unknown.

The level of human intervention (tree harvest, tree pruning, enrichment planting) following buffer establishment will also greatly affect a series of ecosystem services (Table 10). Consequently, managing poplar buffers for intensive biomass production and nutrient exportation, for extensive or semi-intensive wood production, or for riparian forest reconstruction will not lead to the same output in terms of ecosystem service provision (Figure 6). Thus, a complex mosaic of poplar buffers with different management regimes and designs could be created at the watershed level, depending on farm-scale objectives and biophysical characteristics, but also depending on stream rehabilitation targets. Finally, while multiple genotype buffer systems should always be used to improve resilience [55], developing, selecting and spatially positioning the right genotypes for the provision of specific ecosystem services would greatly improve the performance of poplar buffers planted for multi-functionality (Table 10) [27].



Intensive buffer

Management considerations

◊ Whole tree harvest / clear-cutting
◊ Management of stool coppice
◊ Short rotation (5-10 yrs)
◊ High tree density (1000-3000 stems/ha)
◊ Use genotypes with high juvenile productivity
◊ Rotational harvest at landscape level

Key ecosystem services / functions

◊ Biomass, fibre & fodder production***
◊ Nutrient exportation / denitrification***
◊ C storage***
◊ Local climate regulation*
◊ Disturbance regulation*
◊ Habitat provision / biological control*
◊ Cultural services*
◊ Erosion control* / soil formation?

Semi-intensive buffer

Management considerations

◊ Partial & periodic harvest
◊ Medium length rotation (10-20 yrs)
◊ Low tree density (500-1000 stems/ha)
◊ Select most resilient genotypes
◊ Prune trees

Key ecosystem services / functions

◊ Sawlog, fibre. biomass & fodder production***
◊ Nutrient exportation / denitrification***
◊ C storage***
◊ Local climate regulation**
◊ Habitat provision / biological control**
◊ Disturbance regulation**
◊ Erosion control** / soil formation*
◊ Cultural services*

Forest reconstruction buffer

Management considerations

◊ Improve diversity and complexity
(underplanting; maintain or produce deadwood & snags)
◊ Maintain closed canopy (streamside & field side)
◊ Enhance instream habitat (large woody debris addition)
◊ Improve spatial heterogeneity (landscape scale)
◊ Connect to natural upland & riparian habitats

Key ecosystem services / functions

◊ Habitat provision / biological control***
◊ Cultural services (recreational & aesthetic value)***
◊ Local climate regulation***
◊ C storage***
◊ Soil formation & streambank stabilisation***
◊ Disturbance regulation***
◊ Nutrient regulation (denitrification***, N-P storage?)

Figure 6. Examples of the different management options available following hybrid poplar buffer establishment in agricultural riparian zones. Potential levels of ecosystem service or function supply within the different buffer management types are indicated (* low; ** moderate; *** high, ? uncertain).

Table 10. Overview of potential ecosystem service and disservices following the replacement of non-managed herbaceous buffers by hybrid poplar buffers. Management considerations for services optimisation and disservices mitigation are also provided.

Ecosystem Services	Functions, Processes, Structures and Traits Related to Ecosystem Services	Potential Trade-Offs or Disservices	Optimisation and Mitigation Strategies
Regulation			
Non point-source pollution control/water quality protection	• Fast-growth, high water uptake, high N and P concentration in tissues, and perennial nature of poplars allow high rate of nutrient uptake/accumulation and long-term storage in woody biomass [35,40,163].	• Nutrient uptake efficiency may be reduced over the years, as mean annual biomass increment may decline, and as tree mortality occurs.	• Select productive clones with low nutrient use efficiency (high nutrient concentration per unit of dry woody biomass). • Harvest biomass periodically to maintain high nutrient uptake rates and allow N and P exportation offsite [40,165]. • Use high tree density to increase competition for nutrients in the buffer zone. • Include a herbaceous strip at the buffer/cultivated field interface to allow runoff dispersion/infiltration and sediment deposition [166]. • Prune field-edge trees to increase light penetration and improve herbaceous plant growth [30]
	• Introduction of hybrid poplar leaf litter in degraded farm streams can increase instream N and P retention due to bacterial immobilisation [122].	• Leaf litter addition increases total nutrient pool of streams.	• Select clones with high resorption proficiency and low leaf biomass production to reduce N and P losses to stream.
	• Extensive lateral rooting [167,168] allows nutrient capture beneath adjacent pastures and crops.	• Poplar lateral roots can compete with adjacent agricultural crops for water and nutrients [169].	• At the buffer/field interface, plow soil or prune roots with a ripper knife to reduce tree competition with crops near the soil surface [170].
	• Rooting depths greater than 3 m allow nutrient capture at different soil depths and in groundwater [129,171] and could increase depth of active denitrification zone [172]. • Poplar buffers can increase denitrification in the dormant season [44].		• Use long whips planted at >1 m deep in soil to help increase C input at depth and nutrient uptake in groundwater [173].

Table 10. *Cont.*

Ecosystem Services	Functions, Processes, Structures and Traits Related to Ecosystem Services	Potential Trade-Offs or Disservices	Optimisation and Mitigation Strategies
Non point-source pollution control/water quality protection	• Poplar rhizosphere supports microbial community important for bioremediation processes [116]. • Poplars can uptake, store and transform some pesticides [117].		• Use clones having high rates of root exudation and fine root production to increase soil microbial activity and bioremediation [174,175].
	• Instream poplar root growth allows nutrient uptake directly from water in farm streams [43].	• Poplar roots may enter subsurface tile drains and reduce field drainage [43].	• Avoid planting poplars near drainage systems (not within 30 m). • Design drainage system to allow drains to outflow before the buffer zone [20].
	• Riparian buffer zones with tall trees efficiently reduce pesticide drift in water bodies [176].		• Maintain a continuous tree structure and use clones with dense foliage for intercepting pesticide drift.
Local and global climate regulation	• Poplar buffers create a new and fast-growing biomass C sink on farmland [35,163,177]		• Harvest poplar biomass and use bioenergy to displace fossil fuel or produce solid wood products with long life cycles. • Given that C stocks increase with stand age and complexity [178], allow the buffer to age and manage for a multi-layer structure (under-planting and natural regeneration). • Use clones with greater longevity to create a more stable C stock.
	• Poplar buffers improve stream and riparian zone shading [30] and can lower stream temperature [48,179]. • Streamside tree canopy development may reduce GHG emissions by reducing stream and riparian soil temperature [124].	• Linear structures of poplar can shade crops and reduce yields, especially on north side [180]. • Poplars can shade out understory herbaceous vegetation [30] and reduce its runoff interception capacity. • Reduction in periphyton biomass because of tree shading may increase dissolved nutrients in streams [118].	• Near the stream, use clones with a dense canopy and larger crowns, and maintain closed canopy, to maximise light interception and temperature reduction of soil, air and water. • At the field edge, use clones with a small crowns and prune trees to reduce light competition with crops and to improve understory herbaceous growth.
	• Litter and woody debris inputs from riparian trees improve stream C storage.		• Maintain tree canopy to increase terrestrial litter and woody debris inputs to stream. • Select genotypes with slower decaying leaf litter to improve stream C storage.

Table 10. *Cont.*

Ecosystem Services	Functions, Processes, Structures and Traits Related to Ecosystem Services	Potential Trade-Offs or Disservices	Optimisation and Mitigation Strategies
Local and global climate regulation	• The mitigation of agricultural N and P pollution by riparian buffers may improve stream C storage by limiting terrestrial input decomposition [115].		• Maximise nutrient removal in buffers to improve stream C storage.
Disturbance and water regulation	• Tree stems and fallen woody debris reduce flow velocity and flood damages [181]. • Windbreak effect of trees in open areas reduces wind velocity, storm impacts, while enhancing snow accumulation in semiarid regions [182]. • Tree vegetation allows greater infiltration of surface runoff [4,183]. • Decaying tree roots create macropores in streambank soil, which improves water storage capacity during storm events [184].	• Weak mechanical resistance of poplars [185] make them susceptible to extreme climatic conditions. • Fallen trees and branches can obstruct drainage ditches and stream culverts. • Trees can break and fall in cultivated fields or on pasture fences.	• Remove dead/broken trees and woody debris in areas close to infrastructures. • Design new infrastructures to allow coarse woody debris movement in streams [186]. • Select clones with higher stem wood density and smaller crowns for planting in windy, snowy and flood prone areas [28]. • Harvest mature trees to avoid tree breakage.
	• Planted poplars have a similar water yield to hardwood forests, and can reduce peak flow and spring floods on farmland [187]	• In dryer climate or in wetland habitats, planted poplars can adversely affect local water balance because of their high water use [188,189].	• Select clones with high water use efficiency in sensitive habitats (wetland margins, dry climate) [190].
Soil protection and formation	• Streamside poplar plantings improve streambank stability [125,191].	• Riparian afforestation may increase short-term erosion rate along incised channels and contribute to channel widening [192,193].	• Use deep-rooted clones to improve soil stability down to the base of streambanks.
	• Poplar afforestation can increase soil C stocks over the long term [58,62]	• Poplar afforestation can reduce soil C over the short term [43,58].	• Select clones with high fine root and root exudate production rates to increase C input and microbial activity in soil. • Use deep-rooted clones to increase soil C input at depth.
	• Windbreak effect of tree buffers can reduce arable soil erosion [182].		• Maintain a continuous linear tree structure to optimise the windbreak effect [182].

Table 10. *Cont.*

Ecosystem Services	**Functions, Processes, Structures and Traits Related to Ecosystem Services**	**Potential Trade-Offs or Disservices**	**Optimisation and Mitigation Strategies**
Biological control	• Poplar canopy provides a shade barrier reducing riparian zone invasion by shade-intolerant exotic plants [30]. • Poplar canopy can reduce weed biomass in riparian zones [30]. • Poplar buffers can reduce the abundance of meadow vole (*Microtus pennsylvanicus*), a crop damaging mammal [31]. • Linear poplar structures are reservoirs of beneficial insects (predators and parasitoids) in agroecosystems [140].	• Poplar buffers may become suitable habitat for shade-tolerant invasive species, such as glossy buckthorn (*Rhamnus frangula*) [30,194]. • Reduction in understory herbaceous vegetation may reduce runoff dispersion capacity.	• Maintain a closed and continuous canopy to reduce invasion by shade-intolerant exotic plants. • Select clones with a large crowns and dense foliage to increase light interception and reduce edge effect [30].
Habitat Provision			
Refuge and nursery for terrestrial biodiversity	• Poplar buffers and poplar afforestation can increase natural tree regeneration and plant and fungi diversity on farmland [29,30,143,151,195]. • Poplar buffers and poplar afforestation can increase mammal, bird and insect diversity on farmland [31,137–141]. • Planted poplars can serve as nurse stands for mid and late-successional tree species and forest herbs [142,144,196]. • Forest corridors allow vertebrate, insect and plant movements between remnant forest patches in agricultural landscapes.	• Poplar afforestation in natural grassland ecosystems can reduce native plant diversity [197]. • Predators (fox, coyote, wolf) of livestock and crop damaging species (deer, elk) may use tree corridors to travel on farmland [198]. • Heavy poplar browsing by cervids and beaver can results in poor tree survival/establishment [104,163,164,199], and thus poor ecosystem service provision. • Riparian corridor composed of exotic poplars can lead to genetic pollution of native poplar stands [200]. • Poplars are hosts of many diseases and insects [28].	• Optimize spatial and structural heterogeneity and use longer rotations [141,201,202]. • Maintain tree cover at the landscape scale. • Use multiple clones with different tree architectures and longevity. • Use clones that break easily (wide crowns, forked stems, low wood density), cut some poplars down and retain dead trees to provide coarse woody debris and snags. • Notch or girdle living poplars for enhancing woodpecker food sources and habitats [203]. • Under-plant native hardwoods, conifers and riparian/wetland herbs. • Use genotypes with large lateral branches for bird nest placement [204]. • Protect trees with metallic mesh to avoid beaver damage or trap beavers. • Use *Tacamahaca* section related clones to reduce browsing by cervids [104]. • Use large planting stock in wilder areas [205]. • Avoid planting exotic poplars near small isolated natural poplar stands [206], or use native genotypes.

Table 10. *Cont.*

Ecosystem Services	Functions, Processes, Structures and Traits Related to Ecosystem Services	Potential Trade-Offs or Disservices	Optimisation and Mitigation Strategies
Refuge for aquatic biodiversity	• Temperature regulation, improved water quality and clarity by poplar buffers enhance stream biodiversity [48]. • Hybrid poplar litter input can increase stream invertebrate abundance and diversity in farm streams [123]. • Hybrid poplar buffers can become source of large deadwood within a decade [42].		• First, restore natural flow regime in streams, and then reduce contaminant load to stream [162]. • Maintain a closed and continuous canopy near the stream. • Restore instream large deadwood and tree/shrub vegetation overhanging the stream. • Allow stream meandering to improve leaf litter retention and habitat complexity along straightened farm streams [123]. • Because leaf litter quality and decay speed differ with poplar genotypes [207–209], use genotypes with contrasted/complementary litter quality for stream invertebrate enhancement [123].
Production			
Raw materials and energy	• High productivity and versatility of poplar wood is interesting for the production of biomass, pulp and paper, solid wood products and biofuels [76,145]. • Poplars rapidly provide a source of timber for ecosystem engineering.	• Clear-cutting of poplars can cause soil erosion and instream sediment pollution [210]. • Use of heavy machinery for harvest can cause soil compaction [211], which could reduce water infiltration in soil and pollutant trapping efficiency. • Tree harvest can impinge on ecosystem services related to canopy closure (biological control, habitat provision, aesthetic value, *etc.*).	• Use rotational or partial harvest to maintain a tree structure at the landscape level and to reduce erosion [210,212]. • If heavy machinery is used for harvesting, wait for frozen ground to reduce soil compaction [213], and avoid traffic on streambanks. • Select clones with higher wood density and low branch biomass, and prune trees and use a lower stand density to produce high quality logs. • For bioenergy production, select productive clones with a high energy content per unit of biomass.

Table 10. *Cont.*

Ecosystem Services	Functions, Processes, Structures and Traits Related to Ecosystem Services	Potential Trade-Offs or Disservices	Optimisation and Mitigation Strategies
Food	• Poplar foliage and rameal wood can be used as a fodder for livestock, but also as a supplement to increase reproductive capacity [148,149]. • Poplar litter has a positive effect on adjacent farm soil fertility [150]. • The windbreak effect of trees can increase crop yield and offer protection to livestock [182]. • Decaying trees in poplar plantations can be naturally colonized by *Pleurotus ostreatus*, an edible mushroom [151]; poplar logs can also be inoculated with this fungus.	• Poplar leaves can accumulate heavy metals from contaminated soils at concentrations that are harmful for livestock [27]. • Field margin trees can compete with nearby crops for resources. • Buffer establishment can be made at the expense of cultivated areas. • Heavy poplar browsing by livestock will reduce growth and may cause mortality.	• Select clones with higher protein or N content in branches and foliage to feed livestock, and test soil and poplar tissues for heavy metal contamination. • Select clones with smaller crowns to reduce competition for light with crops, prune roots or plough soil at field edge to reduce root competition [170]. • In pastures, fence riparian buffer to avoid livestock damage (ideally with an electric fence).
Bioproducts	• Propolis, which has applications in medicine, health foods and cosmetics, can be produced from different poplar species [146]. • Antimicrobial flavonoids from poplar twigs have applications in plant disease control [147].		• Select genotypes that have a high production of secondary chemical compounds.
Cultural			
Recreation	• Contribution of tree buffer to stream, riparian and terrestrial biodiversity, but also to water quality, could improve recreational value in rural areas (sport fishing, hunting, bird watching, swimming, *etc.*).		• Increase structural heterogeneity and complexity, and plant biodiversity. • Develop access to riparian zones in agricultural areas. • Maintain closed canopy to lower stream temperature and to provide inputs of terrestrial invertebrates. • Maximise nutrient and sediment pollution removal by buffers.
Aesthetic	• Planted floodplain poplars may be seen as beautiful and useful elements of rural landscapes [214].	• Tree buffers may be seen as structures that close up the landscape, obstruct scenic views, and reduce streamside property value [152,215]. • Streamside tree harvesting may be negatively perceived.	• Open scenic views by thinning and pruning, or avoid tree planting obstructing scenic views. • Use a variety of clones with different tree architectures and shades of yellow in their autumn foliage to increase visual quality of farm landscapes.

4. Conclusions

This study has quantified different ecosystem services (C, N and P storage, wood or biomass production, energy production potential, and indirect conservation opportunities) that could be provided by relatively narrow hybrid poplar riparian buffers implemented along deforested farm streams of watersheds with contrasted agricultural land use. Ecosystem service provision potential from such buffers was positively linked to the proportion of agricultural land use within a watershed, as many farm streams are not currently buffered by riparian forests. Additionally, watersheds with greater agricultural land use generally have greater soil fertility, a factor strongly linked with ecosystem service provision per area planted in poplar buffers. Across the studied watersheds, which ranged from 555 to 771 km^2 in area, available stream length for riparian agroforestry ranged from 115 to 439 km. However, for the entire southern Québec region, much greater potential for ecosystem service provision in tree riparian buffers exists along farm streams, as more than 44,000 km of streams and their associated riparian zones were degraded by channel straightening operations [12].

Furthermore, the literature review undertaken in this study strongly suggests that multifunctional poplar buffers could provide a wide array of ecosystem services, especially if they are strategically sized, located and managed, by taking into account the local and regional biophysical and hydrological features of agricultural landscapes. Increasing energetic conversion efficiency of heating systems and improving farmhouse/greenhouse insulation would reduce the biomass required for heating, while the selection of hybrid poplar clones with a high productivity and a high calorific value would improve the energy production potential per km of riparian buffer. Such a multi-level strategy could reduce the need to intensively manage poplar buffers for the sole production of bioenergy, thereby creating opportunities for the use of a certain percentage of such buffers for riparian forest reconstruction or for extensive/semi-intensive biomass or wood production. At the watershed scale, the final output would be the provision of a larger set of ecosystem services in agricultural riparian zones.

However, much work remains to be done in terms of education to make these novel ecosystems socially acceptable among rural communities, land managers and agro-environmental professionals. A financial compensation program could help to attenuate potential disservices related to tree buffer implementation on farmland, since most services provided by such buffers currently have no market value.

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