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Carbon sequestration potential and cost-benefit analysis of hybrid poplar, grain corn and hay cultivation in southern Quebec, Canada

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Abstract Fast-growing trees provide opportunities for carbon (C) sequestration. This study compared the C sequestration potential and cost benefit of four cultivation systems in southern Quebec, Canada. The systems studied included two hybrid poplar cultivation systems, a hybrid poplar and hay intercropping system (111 trees ha^{-1}) and a hybrid poplar plantation (1,111 trees ha^{-1}), and two agricultural systems, grain corn and hay. The C sequestration potential was estimated using the net primary productivity (NPP) approach, which relied on literature values and average yields for the study region. We used the NPP approach to quantify C fixed annually in above- and below-ground biomass, to determine the annual plant residue input to soil from litter, root turnover and root exudates, to estimate the fraction of plant residues stabilized in soil organic C, and to provide a reference value or estimate of C sequestration potential. Costs and benefits of the cultivation systems were assessed using replacement chain and equivalent annual annuity approaches, with alternate discount rates. Estimated C sequestration potential was highest for hybrid poplar grid plantation > hybrid poplar hay intercrop > grain corn > hay. Economic benefits, not accounting for potential benefits of C sequestration, were greatest for grain corn > hay > hybrid poplar-hay intercrop > hybrid poplar grid plantation. We conclude that economic valuation of C sequestration potential is necessary to improve the apparent profitability of tree-based cropping systems in Quebec, Canada. And if afforestation with hybrid poplar is considered as an option for increasing C sequestration on Canadian farms, government policies such as C-trading programs would be necessary to increase the financial attractiveness of hybrid poplar cultivation.

Keywords Agroforestry · Hybrid poplar · Discount rate · Soil organic carbon

Introduction

As part of the worldwide effort to slow the rate of human-induced climate change, the governments of Quebec and Canada are making efforts to reduce greenhouse gas (GHG) emissions. The Canadian government via the Copenhagen Accord committed to reduce GHG emissions by 17 % by 2020, i.e. 731 Mt CO_2 equivalents; ~2 % of global emissions. In the same timeframe, the Quebec provincial government aimed to reduce GHG emissions by 20 %, i.e. below 83.9 Mt CO_2 equivalents; ~14 % of Canadian emissions (MDDEP 2009). The agricultural sector is expected to contribute to these efforts by adopting

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beneficial management practices that would increase soil C sequestration and reduce GHG emissions (Smith et al. 2007). Studies showed that agroforestry systems with *Populus* spp. in temperate regions had C sequestration potential of 18 trees ha^{-1} year^{-1} (Nii-Annang et al. 2009; Tsonkova et al. 2012). In addition, hybrid poplar, both in grid-plantation and intercropped systems with annual crops or pasture, were indicated as a candidate species with C sequestration potential (e.g., Arevalo et al. 2011) that could be financially viable on farms (Dominy et al. 2010; Yemshanov et al. 2005).

The objective of this study was to assess the C sequestration potential and cost benefit of four cultivations systems using the NPP approach and cost-benefit analysis, respectively. The systems studied included two hybrid poplar cultivation systems, a hybrid poplar and hay intercropping system (111 trees ha^{-1}) and a hybrid poplar plantation (1,111 trees ha^{-1}), and two agricultural systems, grain corn and hay.

Materials and methods

Case study: grain corn, hay, hybrid poplar, and hybrid poplar-hay intercrop cultivation systems

For the current study, we relied on literature values and average yields for the southern Quebec region to develop case studies for each cultivation system. A brief description of each cultivation system, including typical management practices, published values from southern Quebec, and assumptions used for this study is provided in the following: grain corn cultivation was assumed to follow conventional, tilled (plowed in fall, harrowed in spring), high input crop management practices. Fertilization recommendations for grain corn in Quebec ranged from 120 to 170 kg N ha^{-1} from urea-based fertilizers (CRAAQ 2010). The hay cultivation system was assumed to constitute a mix of legumes and grasses with a 4-year life span. Based on common practices in southern Quebec, we assumed the field cultivated and seeded with a desired mix of forages in late summer or early spring of the establishment year, subsequently fertilized with 30 kg N ha^{-1} from urea-based fertilizer or organic fertilizer (liquid dairy or hog manure) and harvested (mowing, turning and baling) twice during the growing season (CRAAQ 2010).

Hybrid poplar plantation management varied considerably, depending on the desired end product. In this study, we chose a tree density of 1,111 trees ha^{-1} (3 × 3 m spacing) and a rotation age of 20 years (the time from establishment to harvest), based on literature values for hybrid poplar plantations in Quebec (Cai et al. 2011; Coll et al. 2011; Larcheveque et al. 2011). Higher tree densities have been observed due to narrower grid spacing, e.g., 2 × 2 m, 0.5 × 0.5 m (Benomar et al. 2012). Recommended rotation age for hybrid poplar cultivation in Canada ranged from 10- to 26-years (Thomas et al. 2000), and C accumulation was reportedly maximized with rotations of 20- to 50-years (Paul et al. 2002).

The intercropping system chosen for this study was a hybrid poplar plantation with a tree density of 111 trees ha^{-1} (5 × 5 m spacing) on a 20-year rotation intercropped with hay. A tree density of 111 trees ha^{-1} was reported in silvapastoral system (Thevathasan and Gordon 2004a) as well as in intercropping with annual crops (Graves et al. 2007) such as barley (Peichl et al. 2006), corn, soybean, and winter wheat (Thevathasan and Gordon 2004b). Greater tree density of 518 trees ha^{-1} (Rivest et al. 2010) and 208 hybrid poplars plus 139 hardwoods ha^{-1} (Bambrick et al. 2010) were also reported in the literature for hybrid poplar intercropped with annual crops. Because there was limited data on primary cultivation of hybrid poplar and hay in the scenario chosen for this study, we assumed the MABI of hybrid poplar was similar in the intercropping system as in grid plantation and that intercropped hay management and yield was similar to hay grown as a sole crop with a 4-year cultivation period.

Functional unit and yield of harvestable plant material

A functional unit of 1 ha of arable land was used to compare the different systems in terms of C sequestration potential and cost benefits per common land area unit. Yield values selected for NPP calculations of grain corn and hay cultivation were based on reported yields for southern Quebec, ranging from 6.5 Mg dry matter (DM) ha^{-1} (FADQ 2012) to 9.29 Mg DM ha^{-1} (Institut de la statistique du Québec 2012) in the case of grain corn and from 5.21 Mg DM ha^{-1} (Institut de la statistique du Québec 2012) to 8 Mg DM ha^{-1} (Conseil québécois de plantes fourragères 2002) in the case of hay. The range of yield

Table 1 Importance of grain corn and hay cultivation in Quebec and Canada in terms of acreage (ha) and annual production (Mg DM), and hybrid poplar acreage

	Area (ha)		Production (Mg DM)	
	Quebec	Canada	Quebec	Canada
Grain corn[a]	450,000	1.2×10^6	3,100	10,688.7
Hay[a]	753,000	7.9×10^6	3,844.6	27,735.3
Hybrid[b]	12,000	27,000	NA	NA

DM dry matter; *NA* not available

[a] Data on grain corn and hay were obtained from Institut de la statistique du Québec (2012) and Statistics Canada (2012)

[b] Data for hybrid poplar were obtained from Fortier et al. (2011)

values (5.21–8 Mg DM ha^{-1}) reflects the variation in C sequestration potential due to site-specific growing conditions and management practices (Table 1).

For hybrid poplar, yield values were generated by the Canadian Forest Service SSI Model of Keddy and Joss (personal communication 2012). The SSI methodology generates a continuous index of site suitability values by incorporating environmental variables with a fuzzy logic methodology. Environmental variables included in the SSI Model were precipitation, climate moisture index, growing degree days, drainage, and elevation. Growth curves were generated for four sites in southern Quebec (Napierville, Magog, St-Jean sur Richelieu, Beauharnois-Salabery) that represent areas where hybrid poplar cultivation systems exist in this region. The model assumed that mortality declined with increasing plantation age (2 % for years 0–6, 1 % for years 7–9, and 0.5 % for years 10–20). Crop failure risks such as pests, diseases and fire were not include in the model. Yield projections were generated as stem volume (m^3 ha^{-1}), including stem and bark, but excluding branches. The values were converted into Mg DM using a conversion ratio of 373 kg oven dried m^{-3} (Keddy personal communication 2012). The lowest and highest yield projections were assumed to represent the yield range for southern Quebec (Table 2). Assumed stem yields for a 20-year old hybrid poplar plantation (1,111 trees ha^{-1}) ranged from 340.80 to 574.44 m^3 ha^{-1} (Keddy and Joss personal communication 2012) representing 127.12 to 214.27 Mg ha^{-1}, respectively. These projections were 1.4–1.9 times greater than the average yields of 240–300 m^3 ha^{-1} reported for 20-year old hybrid poplar plantations of different tree densities on fertile sites in southern Quebec (Réseau ligniculture Québec 2012).

In the case of hybrid poplar intercropped with hay, the predicted range of stem yields at 20-years old was 41.88–70.59 m^3 ha^{-1} or 28.12–47.39 Mg DM ha^{-1}. These projections were lower than average yields, 240–300 m^3 ha^{-1} reported for 20-year old hybrid poplar plantations of different tree densities on fertile sites in southern Quebec (Réseau ligniculture Québec 2012). Intercropped hay was assumed to produce half of the average yield of hay produced as a sole crop ($\sim$3.3 Mg DM ha^{-1} year^{-1}). This assumption was justified by the fact that understory biomass production is affected by canopy closure in hybrid poplar systems (Fortier et al. 2011). Similarly, in mature hybrid poplar plantations with 400 trees ha^{-1} ($\geq$25 years), the percentage of diffuse non-intercepted radiation was estimated to be 15–20 % that of an open field (Wall et al. 2010).

If the percentage of diffuse non-intercepted radiation declined to 5 %, net herbage accumulation in the understory pasture was estimated to be 21 % of that in an open field (Wall et al. 2010). Hay biomass production was therefore likely to decrease significantly with canopy closure, but we could not be more precise in predicting the yield due to lack of information on hay yields in hybrid poplar-hay intercropping systems.

Calculations for C sequestration potential, and C in the production systems and soil

The C sequestration potential was estimated with the NPP approach described by Bolinder et al. (2007). Briefly, the NPP approach quantifies C fixed annually in above- and below-ground biomass and determines the annual plant residue input to soil from litter, root turnover and exudates. The C sequestration potential was defined as the fraction of plant residue incorporated into the soil and then integrated into a stable SOC pool with a residence time > 100 years (Fig. 1), considering isohumic coefficients (Bolinder et al. 2007; CRAAQ 2010). The NPP, which represents C gain in a system, is composed of the C associated with the different plant components, expressed as:

$$NPP = C_P + C_R + C_S + C_E \quad (1)$$

where C_P represents C fixed in harvested plant components, i.e. grain, forage or tree bole; C_R is the

Table 2 Carbon (C) content (%), harvest index, root: shoot ratio, YE and yield (Mg DM ha^{-1} $year^{-1}$) values used for the calculation of C sequestration in corn, hay, and hybrid poplar cultivation systems

	Corn		Hay		Hybrid popular	
	Value	Reference	Value	Reference	Value	Reference
C content (%)	0.45	Bolinder et al. (2007)	0.50	Thevathasan and Gordon (2004a)	0.42	Peichl et al. (2006)
Harvest index	0.53	Prince et al. (2001)	1.00	Prince et al. (2001)	–	–
Root: shoot	0.18	Prince et al. (2001)	1.67	Bolinder et al. (2007)	0.21	Thevathasan and Gordon (2004a)
YE	1.00	Bolinder et al. (2007)	0.65	Kuzyakov and Domanski (2000)	–	–
Fine root biomass	–	–	–	–	1.24	Yuan and Chen (2010)
Coarse root biomass	–	–	–	–	0.40	Yuan and Chen (2010)
Yield (Mg DM ha^{-1} $year^{-1}$)	9.40	FADQ (2012)	5.72	Institut de la statistique du Québec (2012)	–	–
	9.29	Institut de la statistique du Québec (2012)	8.00	Conseil québécois de plantes fourragères (2002)	–	–
Intercrop	–	–	–	–	28–47	Keddy and Joss, personal communication 2012
Plantation	–	–	–	–	210–354	Keddy and Joss, personal communication 2012

YE represents the extra C from roots exudates and root turnover relative to recoverable roots

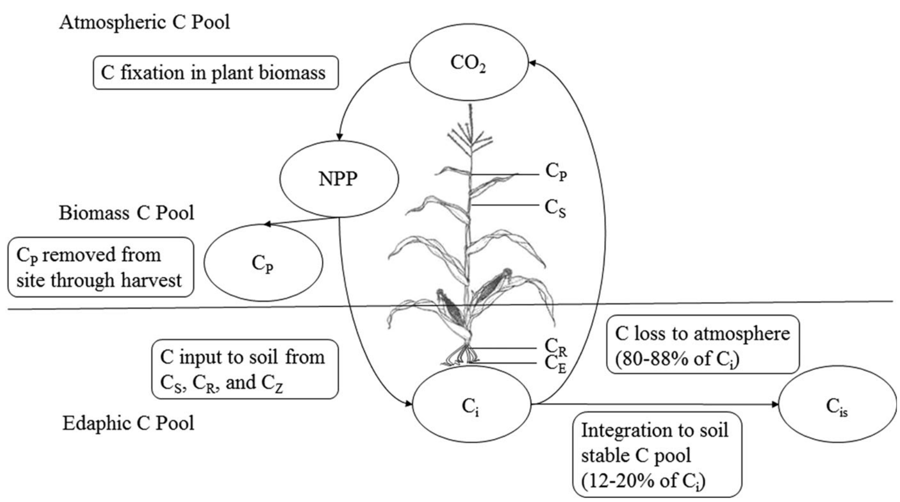

Fig. 1 Net primary production (NPP) based on the concept of Bolinder et al. (2007), showing C_P (carbon in plant product), C_S (carbon in plant residue such as straw and litterfall), C_R (C in coarse and fine roots), C_E (extra-root C from root exudates and root turnover), and interactions of plant C with other components of the C cycle (atmospheric and edaphic C pools)

C in the roots; C_S is the C in the above-ground residues including straw, crop residues or litterfall; and C_E is the C in root products such as root exudates and fine root turnover (Bolinder et al. 2007). Assumptions that applied to crops in this study were provided in Table 2. The C uptake from the different plant components was calculated as follows:

$$C_P = \text{Yield} \times \text{C content} \tag{2}$$

$$C_R = \text{Yield} \times \text{root : shoot} \times \text{C content} \tag{3}$$

$$C_S = \text{Yield} \times (1 - \text{harvest index})/\text{harvest index} \times \text{C content} \tag{4}$$

$$C_E = C_R \times \text{YE} \tag{5}$$

here the harvest index represents the DM yield of harvested product relative to total DM yield of crop and YE represents the extra C from roots exudates and root turnover relative to recoverable roots. The proportion of C input to the soil from various plant fractions was calculated as:

$$C_i = [C_P \times S_P] + [C_S \times S_S] + [C_R \times S_R] + [C_E \times S_E] \tag{6}$$

where C_i represented the annual C input to soil from plants and S was assumed to be the proportion of C in the respective plant fraction that enters the soil, for example, where C_P is C in plant and S_P is the fraction of the C from plant that enters the soil, and the value of S ranges from 0 to 1, representing 0–100 % of a plant fraction incorporated into the soil at the end of a growing season (Bolinder et al. 2007). The crop C sequestration potential C_{is} is then the proportion of C input to soil potentially integrated into the stable soil C pool, assuming 12–20 % of C_i is integrated into the stable soil C pool (CRAAQ 2010):

$$C_{is} = C_i \times 12\,\% \quad \text{to} \quad C_i \times 20\,\% \tag{7}$$

In the case of grain corn, C input to soil was defined as:

$$C_i = [C_P \times 0] + [C_S \times 1] + [C_R \times 1] + [C_E \times 1] \tag{8}$$

In the case of hay cultivation, above-ground crop residues were considered to be absent and roots were assumed incorporated into the soil in the final year of the crop when the field was plowed in preparation for the next crop. The C input to soil was therefore defined as:

$$\text{Throughout hay rotation}: \quad C_i = [C_P \times 0] + [C_S \times 0] + [C_R \times 0] + [C_E \times 1] \tag{9}$$

$$\text{Final year of hay}: \quad C_i = [C_P \times 0] + [C_S \times 0] + [C_R \times 1] + [C_E \times 1] \tag{10}$$

Also, C_E varied for year 1 (establishment year) and for the subsequent years. The mean annual C_i value was estimated by dividing the sum of all C_i values by the number of years in rotation, i.e. in this case, 4 years.

In the case of hybrid poplar, C_P represented C in leafless above-ground biomass and C_S represented the C in litterfall. Because of the perennial nature of hybrid poplar, C_P and C_R were calculated as total biomass at rotation end divided by the age of plantation, following a methodology used by Thevathasan and Gordon (2004a). We estimated biomass allocation to branches because the yield projections included stem and bark, but excluded branches. In the literature, branch biomass was reported to range from 13.7 to 128.5 % of stem biomass (Benomar et al. 2012) in hybrid poplar plantations with similar tree densities and rotation age. However, biomass allocation to branches may also vary with tree density, decreasing with increasing density and tree age (Benomar et al. 2012; Thevathasan and Gordon 2004a). For this study, branch biomass was assumed to represent 125 and 80 % of stem biomass for years 1–10 and years 11–20 for the hybrid poplar-hay intercrop, and 100 % of stem biomass for years 1–10 and 65 % of stem biomass for years 11–20 for the hybrid poplar plantation.

Leaf biomass C was estimated to be 9.7 % of above-ground biomass C, based on values of 0.096 kg DM reported by Swamy et al. (2006) and of 0.098 kg DM by Thevathasan and Gordon (2004a), assuming a similar C content in leaves and above-ground biomass (Thevathasan and Gordon 2004a). Leaf biomass C was calculated annually and then averaged over the plantation life span to generate an annual value. The fine root biomass C was assumed to be equal to leaf biomass C (Thevathasan and Gordon 2004a). As such, C_R was C_P multiplied by the root-to-shoot ratio plus the C content of fine roots. C_E was calculated based on a root turnover rate of 0.4 for coarse roots and 1.24 for fine roots (Yuan and Chen 2010) and excluded rhizodeposits.

In the case of hybrid poplar intercropped with hay, C_R and C_E for the hay were calculated (using Eqs. 4 and 5) five times and then annualized. The hay crop was assumed to be removed and re-established five times for the 20-year period (4-year rotation). Total C_i for the life span of the plantation was calculated as follows:

$$\text{Total } C_i \text{ for life span} = C_R + \text{Sum of annual } C_S + \text{Sum of annual } C_E \tag{11}$$

Then, the annual C_i was estimated by dividing Total C_i for life span by 20 years, i.e. the tree age at time of harvest.

Cost-benefit analysis

To compare economic benefits of two mutually exclusive cultivation systems having unequal lives, i.e. tree versus annual crop, two approaches were used: replacement chain (common life) approach and EAA approach (Brigham and Houston 2010). The common life approach assumes that the cultivation systems can be repeated as many times as necessary to reach a common life span; the net present values (NPVs) over this life span are then compared. The EAA, on the other hand, calculates the annual returns a project would provide if it were on an annuity. The major difference between common life and EAA approaches is that the latter does consider the benefits of reinvestment of net returns obtained annually, while the former approach does not consider the potential returns from reinvestment. Using the common life approach, the net economic benefits of monocropping (agricultural crops, hybrid poplar plantation) and intercropping (hybrid poplar-hay intercrop) systems were then compared by converting the flows of returns and costs into net present value (NPV). The NPV was computed with a set discount rate, considered to be the opportunity cost of an investment. The NPV for a unit area of land with monocropping and intercropping systems was calculated using Eqs. [12] and [13], respectively.

$$NPV^{mono} = \sum_{t=0}^{T} \frac{1}{(1 + r)^t} \times \left(R_t^{mono} - C_t^{mono}\right) \tag{12}$$

$$NPV^{TBI} = \sum_{t=0}^{T} \frac{1}{(1 + r)^t} \left[\theta \times \left(R_t^{crop} - C_t^{crop}\right) + (1-\theta) \times \left(R_t^{tree} - C_t^{tree}\right)\right] \tag{13}$$

where t represents the time period ranging from 0 to T (the end of the time horizon; 20 years); R_t^{mono} represents the revenues obtained per unit of land in a monocropping system; and R_t^{crop} and R_t^{tree} are the revenues per unit of land obtained from crop and tree harvesting, respectively, in an intercropping system. The revenues were calculated as product of respective prices and yields. Similarly, C_t^{mono} represents the cost of cultivation incurred per unit of land under a monocropping system; and C_t^{crop} and C_t^{tree} are the costs of cultivation for a unit of land producing hay and hybrid poplar trees, respectively, in the intercropping system. The C_t^{tree} consisted of establishment costs, including costs of site preparation, planting and tree purchase, and annual maintenance costs such as weeding and pruning. In this analysis, the on-going maintenance costs are discounted back to the establishment period. θ is the proportion of land area in crop cultivation, and therefore $(1 - \theta)$ is the land area used for the tree cultivation; and r is the discount rate. Crop revenues and costs occur each year, but for trees the revenues are generated at the end of the planning horizon, i.e. in the year 'T' with R_t^{tree} remaining zero for most of the years. With the EAA approach, annualized returns were calculated from NPV as follows:

$$Annualized\ returns = \frac{r \times NPV}{\left(1 - (1 + r)^{-n}\right)} \tag{14}$$

where n is duration (years) of a cycle of cultivation system (n = 1 for annual crop). This approach was used by Toor et al. (2012) to compare annualized returns from tree-based intercropping and annual grain cropping systems. The net present values and returns do not include the C sequestration benefits.

Following Toor et al. (2012), a baseline discount rate of 4 % was used in the present study. The returns were, however, evaluated at two alternative values of discount rates (2 and 6 %). The three price levels used in the analysis for corn and hay were minimum, average and maximum values of these crops in the last 5-years (2007–2011), with averaged values considered as the baseline level. The price of poplar ranges from \$10 to 70 m^{-3} (Toor et al. 2012) and the average \$40 m^{-3} was considered as the baseline level. Cultivation costs for grain corn varied between \$1,325 ha^{-1} $year^{-1}$ in reduced tillage an \$1,365 ha^{-1} $year^{-1}$ for conventional tillage, and grain corn had a five year (2007–2011) average yield of 9.4 tonnes ha^{-1} (OMAFRA 2012). The Financière agricole du Québec, which allocates financial compensation to producers in case of low market prices, determined a total cultivation cost of \$1,418 ha^{-1} for grain corn cultivation in 2011, including both variable and fixed costs (FADQ 2012). Market prices for grain corn fluctuated between \$163–\$243 $tonne^{-1}$ in the last 5 years (2007–2012) with a 5-year average price of \$195 tonne-1 (OMAFRA 2012). Financial compensation from the FADQ was included in the cost efficiency calculation for grain corn. Cultivation costs

Table 3 Estimated carbon fixation (Mg C ha^{-1} year^{-1}) associated with harvested product biomass (C_P), stubble residues (C_S), root biomass (C_R), root turnover and root exudates (C_E), and net primary productivity (NPP), as well as CO_2–C equivalent (Mg CO_2–C_{eq} ha^{-1} year^{-1}), and carbon input to soil (C_i) and storage in a stable soil organic C pool (C_{is}) in a grain corn crop, assuming 12–20 % of the C_i was incorporated into a stabilize soil organic carbon pool

Grain corn	C_P	C_S	C_R	C_E	NPP	CO_2–C_{eq}	C_i	C_{is}
Low yield (6.5 Mg ha^{-1} year^{-1})	5.52	2.59	0.99	0.99	7.51	27.52	4.58	0.55–0.92
High yield (9.3 Mg ha^{-1} year^{-1})	7.89	3.71	1.42	1.42	10.73	39.33	6.55	0.79–1.31

CO_2–C_{eq} = NPP × (44 g mol^{-1} CO_2/12 g mol^{-1} C)

for hay crop vary depending on management intensity and were estimated at \$710 ha^{-1} year^{-1} for hay with a five-year average yield of 5.72 tonnes ha^{-1} (OMAFRA 2012). Costs of cultivation included expenses related to seeds, fertilizers, herbicides, custom work for fertilizer and pesticide application, fuel, machine repair and maintenance, rent and labor for the establishment year and custom work for mowing in the subsequent years (OMAFRA 2012). In 2010, the average market price for hay in Ontario, Canada was \$127 tonne^{-1} while the 5-year average for the period of 2006–2010 was \$113 tonne^{-1} (OMAFRA 2012). The price of hay tended to increase from \$111 to \$137 tonne-1 during the five-year period from 2007 to 2011, with an average price of \$122 tonne^{-1} (OMAFRA 2012).

There were a number of possible financial outcomes for hybrid poplar cultivation systems due to the length of the cultivation period and diversity of potential markets. Therefore the cost efficiency of hybrid poplar cultivation systems was calculated using a wide range of values for harvesting costs and fiber prices (Table 3). To allow for comparison with cost efficiencies of annual crops, costs and revenues were annualized based on expected yields for the hybrid poplar systems.

In the case of hybrid poplar-hay intercropping, annualized establishment and maintenance costs for the tree component included site preparation and planting, seedling, weed control and pruning, and were assumed to sum up to \$23 per tree, as estimated by Toor et al. (2012) for hybrid poplar cultivation in a tree based intercropping system in southern Ontario, Canada. Cultivation costs for the hay component of the hybrid poplar-hay intercropping system were assumed to be similar to those for hay as a sole crop, using a value of \$710 ha^{-1} year^{-1} (OMAFRA 2012) but acknowledging that it could be less since hay could be cultivated with less intensive management to avoid disturbing tree roots. Revenues from trees varied depending on yields and end product use, which includes pulp and paper, solid wood and composite wood, and biomass for bio-energy, biofuels, and bioproducts. Revenues were calculated with stumpage prices ranging from \$10 m^{-3} for pulpwood to \$70 for high quality veneer wood (Toor et al. 2012).

Results

C sequestration potential and inputs to soil

The NPP of grain corn in southern Quebec ranged from 7.51 to 10.73 Mg C ha^{-1} year^{-1}, depending on yield (Table 3). An estimated 4.58–6.55 Mg C ha^{-1} year^{-1} from above-ground residues (leaves, stems, and cobs), roots and root turnover was incorporated into soil. We estimated long-term C sequestration in soil (0.55–0.92 Mg C ha^{-1} year^{-1}) for low yielding corn crop and (0.79–1.31 Mg C ha^{-1} year^{-1}) for a high yielding corn crops. The NPP of hay harvested in southern Quebec was 4.96 to 7.62 Mg C ha^{-1} year^{-1}, representing a CO_2 equivalent ranging from 18.18 to 27.92 Mg CO_2 ha^{-1} year^{-1} (Table 4). The annual C input to soil was 2.35 to 3.62 Mg C ha^{-1} year^{-1}. The estimated long term C sequestration in soil was from 0.28 to 0.47 Mg C ha^{-1} year^{-1} for low yielding hay and from 0.43 to 0.72 Mg C ha^{-1} year^{-1} for high yielding hay.

The hybrid poplar plantation had the greatest C sequestration potential of all four systems studied, with a predicted NPP of 19.80–31.01 Mg C ha^{-1} year^{-1} (Table 5). Annual C inputs to soil ranged from 15.40 to 23.58 Mg C ha^{-1} year^{-1}. The estimated long term C sequestration in soil was between 1.85 and 3.08 Mg C ha^{-1} year^{-1} for low yielding plantations and 2.83–4.72 Mg C ha^{-1} year^{-1} for high yielding

Table 4 Estimated carbon fixation (Mg C ha^{-1} year^{-1}) associated with harvested product biomass (C_P), stubble residues (C_S), root biomass (C_R), root turnover and root exudates (C_E), as well as net primary productivity (NPP), CO_2–C equivalent (Mg CO_2–C_{eq} ha^{-1} year^{-1}), and carbon input to soil (C_i) and storage in a stable soil organic C pool (C_{is}) in a hay crop, assuming 12–20 % of the C_i was incorporated into a stabilize soil organic carbon pool

Hay	C_P	C_S	C_R	C_E	NPP	CO_2–C_{eq}	C_i	C_{is}
Low yield (5.2 Mg ha^{-1} year^{-1})	2.61	0.00	1.09	1.27	4.96	18.18	2.35	0.28–0.47
High yield (8 Mg ha^{-1} year^{-1})	4.00	0.00	1.67	1.95	7.62	27.92	3.62	0.43–0.72

CO_2–C_{eq} = NPP × (44 g mol^{-1} CO_2/12 g mol^{-1} C)

plantations. In the hybrid poplar-hay intercropping system, 17–32 % of NPP was from trees and the remainder was from the hay crop, with a total NPP of 9.14–11.18 Mg C ha^{-1} year^{-1} (Table 6). The C inputs to soil ranged from 5.81 to 6.88 Mg C ha^{-1} year^{-1}. The estimated long term C sequestration in soil was between 0.70 and 1.16 Mg C ha^{-1} year^{-1} for low yielding hybrid poplar, and from 0.83 to 1.38 Mg C ha^{-1} year^{-1} for high yielding hybrid poplar.

Cost-benefit analysis

Table 6 shows net present values and annualized net returns under the four cultivation systems (poplar, corn, hay and poplar-hay intercrop) at three discount rate levels and three output price levels. At baseline values (marked by asterisk sign), only corn is expected to generate positive returns. Hay cultivation system was sensitive to the price level and gave positive returns at the price level of \$137 tonne^{-1}. The hybrid poplar gave positive returns at the price level of \$70 m^{-3} and a discount rate of 2 %. Corn system reports positive NPVs and annualized return with all discount rate-corn yield combinations. Overall, the corn system had the highest net returns and thus ranked as the top option for farmers in southern Quebec, followed by hay, hybrid poplar-hay intercrop and hybrid poplar grid plantation systems. The economic ranking of cultivation systems was the same under both NPVs and annualized returns calculations.

Discussion

The NPP approach

Based on estimates of C fixation in plants and transformation of a fraction of plant residues into a stable SOC pool, the NPP approach provided information on the C sequestration potential for four cultivation systems, where greater SOC storage was predicted for hybrid poplar in grid plantation, followed by hybrid poplar intercropped with hay, grain corn as a sole crop, and hay as a sole crop. However, estimating the C fixation and C input to soils relies on several crop- and clone-specific values, as well as site-specific factors such as tillage practices (Arevalo et al. 2011; Popp et al. 2011), soil texture (CRAAQ 2010; Popp et al. 2011), and initial SOC content (VandenBygaart et al. 2003). It should be noted that the NPP approach does not factor in indirect emissions related to farm operations and cultivation inputs; therefore, the NPP approach provides estimates of C sequestration potential other rather than the complete C balance of farms.

Grain corn cropping systems

Estimated C sequestration potential for grain corn in this study (0.55–1.31 Mg C ha^{-1} year^{-1}) was comparable to the C sequestration value of 1.25 Mg C ha^{-1} year^{-1} reported by Popp et al. (2011) for corn cultivation in Arkansas, USA, and the 0.86 Mg C ha^{-1} year^{-1} estimated by Kucharik et al. (2001) for a higher yielding corn crop (10 Mg ha^{-1} year^{-1}) in Wisconsin, USA. Lower values were reported by Quinton et al. (2010), who considered the greater erosion rates and shorter residence time of C in soils associated with cropland than pasture and undisturbed grassland. High input cropland was then estimated to act as a smaller net sink for C sequestration (0.05–0.08 Mg C ha^{-1} year^{-1}), while low input croplands were estimated to be close to C neutral with C uptake ranging from −0.01 to 0.06 Mg C ha^{-1} year^{-1} (Quinton et al. 2010).

Table 5 Estimated carbon fixation (Mg C ha^{-1} $year^{-1}$) associated with harvested product biomass (C_P), stubble residues or litterfall (C_S), root biomass (C_R), root turnover and root exudates (C_E), as well as net primary productivity (NPP), CO_2–C equivalent (Mg CO_2–C_{eq} ha^{-1} $year^{-1}$), and carbon input to soil (C_i) and storage in a stable soil organic C pool (C_{is}) in a hybrid poplar and hay intercropping system (111 trees ha^{-1}) and a hybrid poplar plantation (1,111 trees ha^{-1} $year^{-1}$) in southern Quebec, assuming 12–20 % of the C_i was incorporated into a stabilize soil organic carbon pool

	C_P	C_S	C_R	C_E	NPP	CO_2–C_{eq}	C_i	C_{is}
Hybrid poplar intercropped with hay (111 trees ha^{-1})								
Low yielding (0.78 Mg DM ha^{-1} $year^{-1}$ of trees, 6.6 Mg DM ha^{-1} $year^{-1}$ of hay)								
Poplar	0.59	0.44	0.18	0.94	1.59	5.84	1.56	0.19–0.91
Hay	3.30	0.00	1.09	3.16	7.55	27.67	4.24	0.51–0.85
Total	3.89	0.44	1.27	4.10	9.14	33.50	5.81	0.70–1.16
High yielding (1.32 Mg DM ha^{-1} $year^{-1}$ of trees, 6.6 Mg DM ha^{-1} $year^{-1}$ of hay)								
Poplar	1.00	0.74	0.31	1.59	3.63	13.33	2.64	0.32–0.53
Hay	3.30	0.00	1.09	3.16	7.55	27.67	4.24	0.51–0.85
Total	4.30	0.74	1.39	4.75	11.18	40.99	6.88	0.83–1.38
Hybrid poplar plantation (1,111 trees ha^{-1})								
Low yielding (6.36 Mg DM ha^{-1} $year^{-1}$ of trees, 3.3 Mg DM ha^{-1} $year^{-1}$ of hay)								
Poplar	4.40	3.35	1.35	7.19	16.26	59.63	11.86	1.42–2.37
Total	4.40	3.35	1.35	7.19	16.26	59.63	11.86	1.42–2.37
High yielding (10.71 Mg DM ha^{-1} $year^{-1}$ of trees, 3.3 Mg DM ha^{-1} $year^{-1}$ of hay)								
Poplar	7.42	5.60	2.28	12.12	27.47	100.71	20.04	2.40–4.01
Total	7.42	5.60	2.28	12.12	27.47	100.71	20.04	2.40–4.01

CO_2–C_{eq} = NPP × (44 g mol^{-1} CO_2/12 g mol^{-1} C)

Yield values include stem and bark but exclude branches

Hay cropping system

For hay, the C sequestration predicted by the NPP method (0.28–0.72 Mg C ha^{-1} $year^{-1}$) is tended to be lower than other values reported in the literature Thevathasan and Gordon (2004a) estimated C sequestration potential of 0.99 Mg C ha^{-1} $year^{-1}$ for pasture in southern Ontario. Kucharik et al. (2001) reported a C sequestration potential of 0.745 Mg C ha^{-1} $year^{-1}$ for high productivity grasslands in southern Wisconsin. The difference in C sequestration potential between hay and grain corn may be explained in part by low management intensity and lower productivity of hay crop (Institut de la statistique du Quebec 2012), which resulted in lower C_P values for hay. Also, crop residues were considered nonexistent in the hay crop while the grain corn crop residues contributed an estimated 2.59–3.71 Mg C ha^{-1} $year^{-1}$ (Table 3).

Hybrid poplar grid system

Comparing the C sequestration potential in this study (Table 5) with results from the literature is difficult because of differences in parameters such as tree density, age of plantation, and growing conditions. In the current study, hybrid poplar in plantation gave a total C input ranging from 19.08 to 31.01 Mg C ha^{-1} $year^{-1}$, with the tree component contributing 82–89 % of this amount. Potential long-term C sequestration in soil ranged from 1.85 to 4.72 Mg C ha^{-1} $year^{-1}$ depending on growing conditions, and this is in the same range as Arevalo et al. (2011), who reported a soil C accretion rate of 2 Mg C ha^{-1} $year^{-1}$ for a 4-year old hybrid poplar plantation with 1,600 trees ha^{-1}. Overall, our results suggest a greater long-term C sequestration potential for hybrid poplar plantations than for corn and hay cultivation systems. Studies assessing C balance of hybrid poplar in plantations suggested that hybrid poplar plantations act as net C source in the first 2 years (Arevalo et al. 2011) and 4 years (Cai et al. 2011) with defined turning points and break-even points. Turning points (when the ecosystem becomes a C sink) were reported to be reached at year 2 (Arevalo et al. 2011), while break-even points (when C stored in equals C previously released) were reported to be attained at year 3 (Cai et al. 2011) and at year 4 (Arevalo et al. 2011).

Table 6 Net present values and annualized returns under the four production systems at various discount rates and price levels

Production system and price	Net present value ($)			Annualized net returns ($)		
	r = 2 %	r = 4 %*	r = 6 %	r = 2 %	r = 4 %[a]	r = 6 %
Hybrid poplar						
$10 m^{-3}	−21,632	−22,876	−23,706	−1,323	−1,683	−2,067
$40 m^{-3a}	−10,034	−15,011	−18,333	−614	−1,104	−1,598
$70 m^{-3}	1,563	−7,146	−12,959	96	−526	−1,130
Poplar-hay[b]						
$10 m^{-3}	−2,980	−287	−2,795	−182	−211	−244
$40 m^{-3a}	−1,555	−1,905	−2,135	−95	−140	−186
$70 m^{-3}	−130	−938	−1,475	−8	−69	−129
Hay						
$111.2 tonne^{-1}	−1,441	−1,391	−1,337	−72	−71	−70
$122.0 tonne^{-1a}	431	−551	−628	−12	−12	−11
$136.6 tonne^{-1}	934	584	330	70	69	67
Corn						
$163.0 tonne^{-1}	1,394	773	327	114	109	105
$195.5 tonne^{-1a}	6,389	4,925	3,831	419	403	388
$242.6 tonne^{-1}	13,629	10,942	8,909	861	829	798

[a] Represent baseline levels of discount rates (r) and prices

[b] Only the price of poplar is allowed to vary in the poplar-hay intercrop system; hay price is assumed to be constant at baseline level of $122.0 tonne^{-1}

Hybrid poplar intercropped with hay

The similarity between C_{is} in the hybrid poplar-hay intercropping system and in the corn cultivation system (0.55 to 1.31 Mg C ha^{-1} year^{-1}; Tables 3 and 5) is consistent with the findings of Oelbermann et al. (2006), who found no difference in SOC pools between 19 year-old poplar alley-cropping and sole crop. The C_{is} in the intercropping system was greater than C_{is} for hay as sole crop (0.28–0.72 Mg C ha^{-1} year^{-1}), assuming that the presence of trees does not cause an important reduction in hay yields during a 20-year period, as found by Thevathasan and Gordon (2004a). The presence of trees may also impact soil biota and environmental parameters (Lacombe et al. 2009), which could, in turn, influence C sequestration in soil.

Cost-benefit analysis

When excluding C benefits, corn cultivation showed the highest cost benefits compared to other cultivation systems considered in the current study. Hybrid poplar grid plantation was the most unprofitable followed by the hybrid poplar-hay intercrop and sole hay systems, as reflected by the NPVs and annualized returns. This is due to the fact that hybrid poplar has high maintenance costs every year during its cultivation, and the returns are realized only at the end of a lengthy growth period, i.e. 20 years in this study. Sensitivity analysis of economic models agree on the importance of key biological and economic variables that affect the outcome of cost-benefit analysis, such as site suitability (McKenney et al. 2006), establishment and management costs (Dominy et al. 2010; Keča et al. 2012), agricultural opportunity costs. McKenney et al. 2006; Dominy et al. 2010), and discount rates (Keča et al. 2012; Streed 2002; Toor et al. 2012; Yemshanov et al. 2012).

The profitability of afforestation with hybrid poplar appears to be highly dependent on the discount rate considered in the economic analysis. In the current study, positive returns was achieved at the price level of $70 m^{-3} and a discount rate of 2 %. Looking at potential profitability of hybrid poplar at different sites, Keča et al. (2012) obtained positive NPV at all sites with a 4 % discount rate, a positive NPV only on sites best suited for hybrid poplar cultivation with a 6 % discount rate, and a negative NPV on all sites with an 8 % discount rate. Streed (2002) found that hybrid poplar cultivation for bioenergy was profitable on marginal land only when the interest rate was lower than 5 % and producers received cost-share payments. McKenney et al. (2010) suggest a positive net present value (NPV) of $420 ha^{-1} for an afforestation scenario in southern Ontario with a real discount rate of 4 % (McKenney et al. 2010).

Based on the data presented in this study, if we take difference of annualized returns per ha of corn and poplar-hay system, we can determine the value of C ($403 − (−$140) = $543 ha^{-1}) at baseline values of discount rates and prices (Table 6), indicating that C needs to be valued at $543 ha^{-1}. Similarly, the difference of annualized returns per hectare for corn and poplar only systems would be $403 − (−$1,104) = $1,507 ha^{-1} at baseline values of discount rates and prices (see Table 6). So the C ha^{-1} for these systems needs to be valued at $1,507 ha^{-1}. Divide the C units by C value for the respective system to get the value of each C units.

Conclusions and future research

Within the cultivation systems evaluated, our results showed that hybrid poplar in a plantation has the highest C sequestration potential, followed hybrid poplar intercropped with hay, grain corn as sole crop, and hay as sole crop. We note that the hybrid poplar cultivation systems offered the widest range of possible financial outcomes, given the potential end uses and markets for hybrid poplar wood and the yield variability predicted in southern Quebec. Grain corn had highest economic benefits of the systems studied, while hay offered lower cultivation cost than both hybrid poplar-hay intercrop and hybrid poplar grid plantation systems. Comparing the estimated C sequestration values from the NPP approach of four cultivation systems with literature values confirms the reliability of the NPP methodology for grain corn, hay and hybrid poplar cultivation. However, experimental data would confirm the appropriateness of assumptions made, especially in the case of hybrid poplar-hay intercrop system. We conclude that economic valuation of C sequestration potential is necessary to improve the apparent profitability of tree-based cropping systems in Quebec, Canada. And if afforestation with hybrid poplar is considered as an option for increasing C sequestration on Canadian farms, government policies such as C-trading programs would be necessary to increase the financial attractiveness of hybrid poplar cultivation.

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