



Increasing tree productivity does not translate into greater soil organic carbon storage

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ABSTRACT

Increasing soil organic carbon (SOC) storage is one of the promising solutions to mitigate climate change. Fast-growing trees are a potential tool in this context as they rapidly accumulate C in their biomass and could transfer more organic matter (OM) into the soil. However, the relationship between aboveground productivity and SOC storage remains poorly understood. Five clones with different growth rates were selected from a 14-year-old hybrid poplar plantation located in New Liskeard, ON, Canada. We collected soil cores at 87.5 and 175.0 cm distance from the stem and at 0–20, 20–40 and 40–60 cm soil depth for soil C concentration analysis. The most productive clone DN2 (*Populus deltoides* × *P. nigra*) stored less SOC (83 Mg ha⁻¹) between 0 and 60 cm depth than the mid-productive clones 1079 (*Populus* × *jackii* (*P. balsamifera* × *P. deltoides*)) and 915005 (*P. maximowiczii* × *P. balsamifera*) (95 and 96 Mg ha⁻¹ respectively), while the least productive clone 747210 (*P. balsamifera* × *P. trichocarpa*) also had a lower SOC stock (85 Mg ha⁻¹) compared to the other clones, but not significantly. There was no relationship between aboveground productivity and SOC stocks and total SOC stocks increased by 6 % when the sampling distance was closer to the tree stems. The difference in SOC stocks between clones was mostly observed at the 20–40 cm depth suggesting the significant effect of roots on SOC storage. Soil C/N ratios were significantly different between clones at 0–20 and 20–40 cm depths suggesting differences in OM decomposition rates between clones. There could be a trade-off between aboveground productivity and litter decomposition rate to increase SOC storage.

1. Introduction

One of humanity's most significant challenge is coping with the consequences of global warming mainly caused by increasing global atmospheric CO₂ emissions (IPCC, 2021). Climate change has led to an increase in forest disturbances, such as wildfires and insect outbreaks, that have contributed to the decline and mortality of many forest ecosystems (Anderegg et al., 2015; Balshi et al., 2009; Cohen et al., 2016; Hogg et al., 2002; Parry et al., 2003). To mitigate this, the international "4 per 1000" initiative aims to increase soil organic carbon (SOC) in the top 30 cm of soil annually by four per mil to offset annual anthropogenic CO₂ emissions (Derrien et al., 2016; Minasny et al., 2017). Soil C stocks represent approximately 60 % of the ecosystem C stock in boreal forests, compared to 50 % in temperate and 32 % in tropical forests (Pan et al.,

2011). The elevated SOC in forest ecosystems could come from higher organic matter (OM) inputs derived from litter accumulation, root turnover and root exudation (Derrien et al., 2016; Schmidt et al., 2011; Sokol et al., 2019). In this context, establishing fast-growing tree plantations to create additional soil C sinks has received increased interest in recent years (Chomel et al., 2014; Meifang et al., 2017; Qian et al., 2022; Truax et al., 2018).

Fast-growing plantations such as intensively managed hybrid poplar (*Populus* spp.) are being used around the world to rapidly produce wood biomass on smaller land areas compared to native forests. A significant amount of C is rapidly stored in above and belowground biomass of these trees (Dewar and Cannell, 1992; Tuskan and Walsh, 2001; Weslien et al., 2009) and it is regularly argued that these plantations could be used to increase organic C in soils due to rapid litter accumulation and

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fast root turnover (Block et al., 2006; Chomel et al., 2014; Dewar and Cannell, 1992; Sartori et al., 2007). As an example, Peichl et al. (2006) found that after 13 years, soil C stocks (78.5 Mg ha^{-1}) under 17.6 m – high hybrid poplar trees were more than 16 % greater than those found in a spruce plantation of the same age with 6.3 m high trees. However, roots of fast-growing species can also have faster respiration rates and be decomposed more rapidly compared to those of slow-growing species (Comas et al., 2002; De Deyn et al., 2008; Kane et al., 2005). Furthermore, variability in aboveground productivity has been widely documented for *Populus* genus (Laureysens et al., 2005, 2004; Truax et al., 2014, 2012). Consequently, it is not clear how variation in aboveground productivity among fast-growing trees impacts SOC accumulation and storage.

SOC concentration in the upper soil horizons, where organic matter inputs from leaf litter and roots are more abundant, is generally greater than in deeper soil layers (Howlett et al., 2011; Moreno et al., 2005). However, the deep soil can also contribute significantly to C storage due to their high storage capacity and their importance on long-term C stabilization via interactions with the soil mineral phase (Rumpel and Kögel-Knabner, 2011). As hybrid poplar roots can reach 1 m depth, they could release and accumulate C in deep soil layers relative to shallow-rooted species (Dickmann et al., 1996). Considering that fine root biomass varies significantly among poplar clones and among soil layers (Al Afas et al., 2008), the vertical distribution of SOC may differ for each clone. Furthermore, SOC distribution may also vary horizontally, as the influence of a tree on its surroundings is limited spatially. For example, SOC stock was greatest underneath the tree canopy and decreased with distance in an oak forest of central-western Spain due to the fact that tree canopy contributes to litter inputs (Howlett et al., 2011). However, others also found that SOC stocks do not always differ with distance from trees (Oelbermann and Voroney, 2007; Peichl et al., 2006).

The main objective of our study was to determine if SOC stocks at different soil depths increase with aboveground productivity using a hybrid poplar plantation containing several clones with different growth rates. We secondary tested the effect of distance from trees on SOC stocks. We expected that the most productive clones would store more C in the soil and that SOC would increase with decreasing sampling distance from the stems.

2. Materials and methods

2.1. Site description

The study was performed in a hybrid poplar plantation established on agricultural land at the New Liskeard Agricultural Research Station in North-Eastern Ontario, Canada ($47^{\circ}31'15'' \text{ N}$, $79^{\circ}39'52'' \text{ W}$). Based on 29-year data (1981–2010, Earlton station), this region has a humid continental climate with an average daily temperature of 2.6° C and an average annual precipitation of 786 mm (576 mm rain and 222 cm snow) (Environment Canada, 2021). The soil is characterized by a clay loam texture (Yan et al., 2019) and classified as a Humic Gleysol by Canada Soil Survey Committee (1987) or as Gleysols according to the IUSS Working Group WRB (2015). The regional surficial geology is characterized by clays and lacustrine sands derived from post-glacial Barlow Lake (Rowe, 1972).

The experimental field was ploughed in October 2006 and cross-cultivated with disks followed by herbicide applications in spring 2007 (Roundup™). Hybrid poplar trees were planted in spring 2007 at a $3.5 \text{ m} \times 3.5 \text{ m}$ spacing ($816 \text{ stems ha}^{-1}$) and fertilized with NPK 18-23-18 (110 g tree^{-1}), at a rate of 89.76 kg ha^{-1} . Annual weed control was provided by cultivating between rows with disks followed by herbicide application between trees for the first two years after plantation establishment. The experimental design consisted of 3 replicate blocks each with 8 monoclonal plots of 100 trees (10 rows \times 10 trees) randomly distributed within blocks.

We selected 5 clones within the 8 planted ones according to their

productivity after 14 years, from the least productive to the most productive. The selected clones were: 1079 (*Populus* \times *jackii* (*P. balsamifera* \times *P. deltoides*)), 747210 (*P. balsamifera* \times *P. trichocarpa*), 915005 (*P. maximowiczii* \times *P. balsamifera*), 915319 (*P. maximowiczii* \times *P. balsamifera*) and DN2 (*P. deltoides* \times *P. nigra*).

2.2. Clone productivity

Field measurements were taken in July 2021 when the trees were 14 years old. We measured diameter at breast height (DBH) and tree height (H) in a 6×6 tree subplot for each monoclonal plot using a dendrometric tape and a Vertex 5 Hypsometer. We subsequently estimated stem volume (outside of the bark) of each tree from using the allometric equation established by Truax et al. (2014):

$$V = 0.1014 \times DBH^{2.5562} \quad (1)$$

where V is the stem volume outside of the bark (dm^3) and DBH is the diameter at breast height (cm). In this study, the average annual growth rate ($\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was used to estimate the productivity of each hybrid poplar clone and was calculated by dividing total stem volume by subplot area and plantation age (Truax et al., 2014, 2012).

2.3. Soil sampling and carbon analysis

Soil sampling was done in the same subplot (6×6 trees) selected for dendrometric measurements. For each subplot, soils were sampled between two trees in a systematic way. We collected the soil cores at two distances (87.5 cm (quarter) and 175.0 cm (center)) from a stem and at 3 soil depths (0–20, 20–40 and 40–60 cm) using a PVC cylinder (10 cm diameter and 20 cm length). A total of 180 soil cores (2 trees \times 2 distances \times 3 soil depths \times 5 clones \times 3 blocks) were collected in plastic bags, stored in a cooler and brought to the laboratory for further analysis.

We first removed and weighed pebbles and broke the soil into small pieces to facilitate air drying using 8 mm sieves. The pebble mass accounted for only 0.3 % of the soil mass at most due to the clay loam texture of the soil. All air-dried soil samples were then ground to 2 mm before analysis. One soil subsample from each clone in each block and at each depth ($n = 45$) was selected to measure the average soil pH of the site. We measured the pH of 10 g of air-dried soil subsamples ($< 2 \text{ mm}$) in 20 mL of 0.01 M CaCl_2 with a pH meter (Hach Sension + MM374). The soil pH values reached $6.9 (\pm 0.2)$, $7.4 (\pm 0.2)$ and $7.6 (\pm 0.1)$ for the 0–20, 20–40 and 40–60 cm depths respectively, suggesting the presence of inorganic C in our samples. Therefore, the C in our samples could not be considered as SOC solely. Accordingly, we followed the method of Kreyling et al. (2013) to distinguish organic and inorganic C from our soil samples. Subsamples (5 g) were heated for 4.5 h in a muffle furnace at 450° C to combust OC. Heat-treated and non-heat-treated subsamples were analyzed for total C and nitrogen (N) concentrations by dry combustion (Vario MAX cube; Elementar, Langensfeld, Germany). Carbon in the non-heat-treated subsamples was considered as total C while C in the heat-treated subsamples was considered as inorganic C. Thus, we calculated the organic C concentration by subtracting the inorganic C concentration from the total C concentration.

Another 10 g subsample of each soil sample was oven-dried (105° C , 72 h) to calculate its oven-dried mass. We then calculated the soil bulk density (BD, g. cm^{-3}) by using the Eq. (2) (Poeplau et al., 2017), which is as follows:

$$BD = (\text{mass}_{\text{sample}} - \text{mass}_{\text{pebbles}}) / (\text{volume}_{\text{core}} - \frac{\text{mass}_{\text{pebbles}}}{\rho_{\text{pebbles}}}) \quad (2)$$

Where $\text{mass}_{\text{sample}}$ and $\text{mass}_{\text{pebbles}}$ are the masses (g) of oven-dried samples and pebbles, respectively, $\text{volume}_{\text{core}}$ is the soil core volume (cm^3), and ρ_{pebbles} which is equal to 2.6 g cm^{-3} is the approximate density of pebbles (Don et al., 2007).

SOC stock (Mg ha^{-1}) for each depth was calculated by using the Eq.

(3) (Poeplau et al., 2017), which is as follows:

$$SOC_{stock} = SOC_{concentration} \times BD \times d \times (1 - \delta) \times 0.1 \quad (3)$$

where *SOC concentration* is the soil organic carbon concentration (g kg⁻¹), *BD* is the soil bulk density (g. cm⁻³), *d* is the depth (cm) and δ is the pebble volume fraction (%/100). For the total soil profile, the *total SOC stock* is equal to the sum of the *SOC stock* for each soil depth. As we suggest the presence of inorganic C in our soil samples and we do not have the soil organic N values, we calculated the soil C/N ratios by dividing organic C by total N concentrations of the whole soil.

2.4. Statistical analysis

All statistical tests were performed using the statistical software R version 4.1.1 (R Development Core Team, 2013). Analysis of clone and distance effects were estimated using linear mixed models with the lme4 package and lmerTest package in R where block was considered as random effect (Bates et al., 2014; Kuznetsova et al., 2017). We calculated the estimates (SOC and total N concentrations, C/N ratio, bulk density, and SOC stock) for each clone by the average values in both distances (87.5 and 170 cm). We selected models with smallest AICc (Akaike Information Criterion) with the aictab() function. To validate each model, we checked model assumptions (independence of residuals, equality of variance (homoscedasticity), and normality of residuals) by diagnostic graphs and Shapiro-Wilk tests. The model assumptions have been respected without data transformation. The predictor effect was significant when the probability level (p) was below the theoretical probability level $\alpha = 5\%$. The emmeans package in R was used as a *post-hoc* method to make pairwise comparisons when a significant effect was found for a variable (clone or distance) (Lenth et al., 2018). Regression models were used to determine the relationship between clone growth rate and total SOC with the function lm() in R. The models were selected based on their relevance, i.e. adjusted coefficient of determination R² closer to 1 and lower p-value.

3. Results

3.1. Tree productivity and total SOC stocks (0–60 cm)

Mean tree characteristics (DBH, tree height and stem volume) for each clone were summarized in Table 1. Clone DN2 was the most productive, clone 747210 was the least productive and clones 915319, 1079 and 915005 had intermediate growth rates ($p < 0.001$, Fig. 1). All hybrid poplar clones stored an average of 82.9 to 95.7 Mg ha⁻¹ to a 60 cm depth. There were significant differences in total SOC stocks (0–60 cm) between clones ($p = 0.004$). The most productive clone (DN2) stored 13 % less SOC than the mid-productive clones 1079 and 915005 to a 60 cm depth (Fig. 2). The least productive clone (747210) also stored less SOC, but the difference was not significant from that of the

Table 1
Mean tree characteristics (diameter at breast height, tree height and stem volume) for each clone.

Clone	DBH (cm)	Height (m)	Stem Volume (dm ³ tree ⁻¹)
747210	17.40 (±0.46)	d 16.31 (±0.22)	d 174.67(±23.42)
915005	19.67 (±0.26)	c 18.32 (±0.17)	cd 212.66(±6.76)
1079	21.09 (±0.27)	b 19.78 (±0.20)	b 253.19(±7.59)
915319	22.14 (±0.24)	b 21.36 (±0.19)	a 284.39(±7.70)
DN2	23.76 (±0.36)	a 21.35 (±0.20)	a 346.55(±12.88)

Standard errors of the mean (SEM) are given in parentheses. Different letters indicate significant differences between clones ($p < 0.05$).

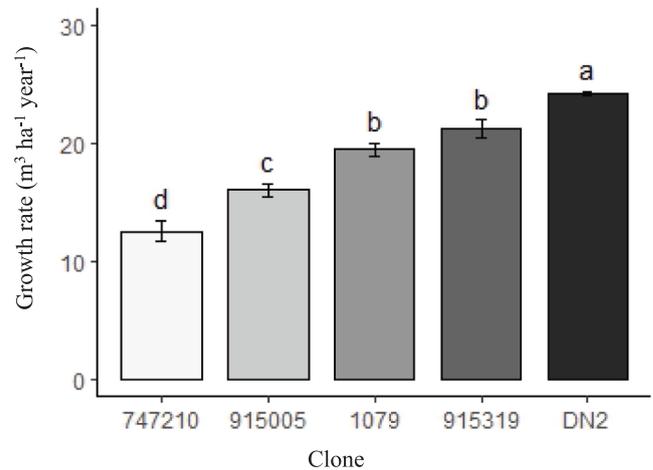


Fig. 1. Mean (±SEM) clone growth rate after 14 years of planting. Different letters indicate a significant difference between clones ($p < 0.05$).

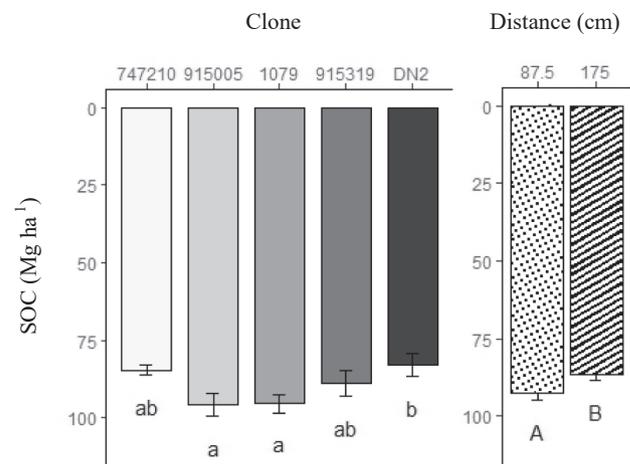


Fig. 2. Mean (±SEM) of total SOC stock in the first 60 cm of depth for each clone and for each distance from the stem. Different lower-case letters indicate a significant difference between clones and different upper-case letters indicate a significant difference between distances ($\alpha = 0.05$). Clones are arranged in ascending order of their growth rates.

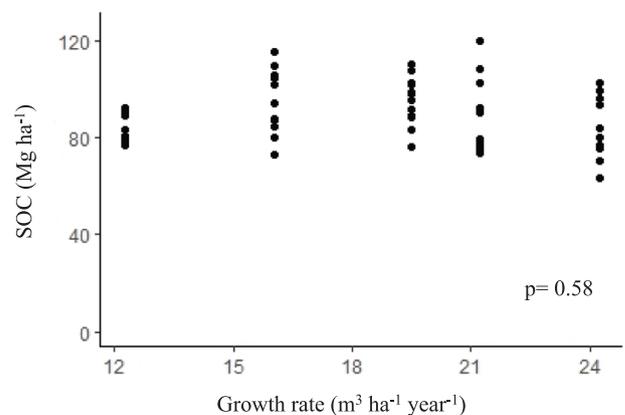


Fig. 3. Relationship between growth rate and SOC stock in the first 60 cm of depth.

other clones. Consequently, there was no significant relationship between clone productivity and total SOC stocks ($p = 0.58$, Fig. 3). Total SOC stocks increased by 6 % when the sampling distance was closer to the stem ($p = 0.03$, Fig. 2).

3.2. SOC in each depth

SOC stocks were greater within the first 20 cm layers of the soil and decreased rapidly with increasing depth for all clones (Fig. 4). However, SOC stocks at the 0–20 cm depth were not significantly different between clones at the significance level of $\alpha = 0.05$. The difference in SOC stocks between clones was only observed at the 20–40 cm depth ($p = 0.01$). The mid-productive clones 1079 and 915005 stored greater SOC i. e., $27.2 (\pm 2.8)$ and $27.1 (\pm 3.7)$ Mg ha^{-1} , respectively, at the 20–40 cm depth compared to the most productive clone ($17.2 (\pm 2.7)$ Mg ha^{-1}) (Fig. 4). At the 40–60 cm layer, SOC stocks were significantly low and similar for all clones ($p = 0.14$). Relationships between aboveground productivity and SOC stocks at each depth were not significant (p greater than 0.05 for all depths).

3.3. Soil organic C concentration, C/N ratio and bulk density

There were significant differences in SOC concentrations (i.e., g kg^{-1}) between clones at depths of 0–20 ($p < 0.001$) and 20–40 cm ($p = 0.04$). SOC concentrations under clones DN2 and 747210 were lower than those under clones 1079 and 915005 at the 0–20 cm depth and SOC concentration under clone DN2 was lower than that under clone 1079 at the 20–40 cm depth (Table 2). Significant differences in total soil N concentration between clones were also observed at depths of 0–20 ($p < 0.001$) and 20–40 cm ($p < 0.05$) and the same trend as SOC concentration was observed (Table 2).

Soil C/N ratios were significantly different between clones at depths of 0–20 ($p < 0.001$) and 20–40 cm ($p = 0.04$). The least productive clone (747210) and clone 915319 had lower soil C/N ratios than clone 1079 in the topsoil (0–20 cm) while the most productive clone (DN2) had lower soil C/N ratio than clone 915005 at 20–40 cm depth (Table 2). In the 40–60 cm layer, the soil C/N ratios of all clones were similar (Table 2). In addition, there was no significant difference in soil bulk density between clones at all depths (0–20 cm ($p = 0.07$); 20–40 ($p = 0.49$) and 40–60 cm ($p = 0.92$)).

4. Discussion

4.1. Importance of productivity on SOC

SOC storage is determined in part by the balance between C inputs from above- and belowground biomass and root exudates against C losses through microbial decomposition, root respiration and leaching (Epron et al., 2006; Martí-Roura et al., 2019; Schmidt et al., 2011). In our study, the most productive clone stored less SOC than the mid-productive clones to a depth of 60 cm. This result is inconsistent with our hypothesis and other studies that predicted increased soil carbon storage with increasing aboveground productivity (Peichl et al., 2006; Weslien et al., 2009). Higher productivity clones could supply more labile litter and root biomass. These greater labile C inputs (root exudation and litterfall) might have created favorable conditions for soil microbes for decomposition and enhanced the priming effect which is the stimulation of decomposition of recent as well as old or stable organic matter (Cheng et al., 2014; Jansson and Hofmockel, 2020). The low soil C/N ratios at the 20–40 cm depth could also indicate the priming effect in this clone. For example, Dijkstra et al. (2006) demonstrated that the priming effect was positively related to plant productivity and in a study by Mack et al. (2004), SOC stock decreased with increased aboveground productivity (with increased nutrient availability through fertilization) in the Alaskan tundra due to accelerated decomposition. Other studies showed that increasing aboveground productivity of poplars did not enhance soil C stocks (Meifang et al., 2017; Qian et al., 2022). In addition, long-term litter manipulation experiments have shown that doubling litter inputs does not necessarily increase SOC stocks, potentially due to enhanced decomposition of new inputs and priming of old SOC (Lajtha et al., 2018).

We also observed that the least productive clone likewise stored less organic C to a depth of 60 cm, but not significantly. The soil under this clone could receive less litter input as it produced less aboveground biomass. This clone also had lower soil C/N ratios in the topsoil (0–20 cm), indicating faster litter decomposition rates (Berg et al., 1998; Taylor et al., 1989; Yu et al., 2019). However, further measurements are needed to confirm the litter decomposition rate of each clone as the soil C/N ratio is simply an indicator. For fast-growing trees, aboveground productivity could promote SOC input, but there could be a trade-off between tree productivity and litter decomposition rate to increase SOC storage.

4.2. Potential contribution of roots to C storage in the deep soil

After 14 years of planting, we found that the differences in SOC stocks between clones were mostly observed at the deeper 20–40 cm depth. As Rumpel and Kögel-Knabner (2011) emphasized the importance of plant roots as significant sources of OM in deep soil, differences in root traits may have led to the difference observed in SOC stock between clones. Several studies reported a significant variation in fine root biomass and production among different poplar clones due to the parental genetic difference (Al Afas et al., 2008; Dickmann et al., 1996; Lukac et al., 2003). This fine root production variation may have contributed to the variation of SOC stocks between clones. As hypothesized, we also found that SOC stocks increased with the decrease in distance between sampling point and the stem. The soil located directly below the tree canopy receives more OM because of higher litterfall, and additionally, due to abundant roots present near the main stem (Howlett et al., 2011). Changes in soil microclimatic conditions under trees could also affect SOC stocks as decreasing soil temperature could reduce OM decomposition and promote SOC storage (Ding et al., 2014; Zhang et al., 2016).

The most productive clone (DN2) could have produced roots that accelerated the decomposition rate and reduced SOC stocks. It could have more fine roots than the other clones since a clone issued from the same crossbreed (*P. deltoides* × *P. nigra*) had the highest fine root

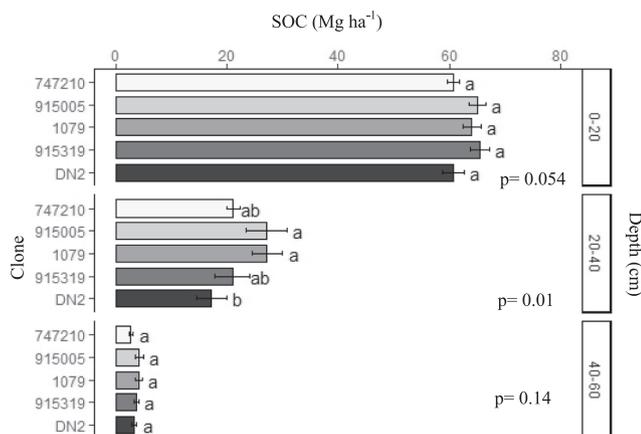


Fig. 4. Mean (\pm SEM) of SOC stocks for each clone at each depth. Different letters indicate significant differences between clones at each depth ($p < 0.05$). Clones are arranged in ascending order of their growth rates.

Table 2
Mean (\pm SEM) SOC concentration, C/N ratio and bulk density (BD) of the soil at each depth.

Depth (cm)	Clone	SOC concentration (g kg ⁻¹)		Total N concentration (g kg ⁻¹)		Soil C/N		BD (g cm ⁻³)	
0–20	747210	29.08(\pm 0.54)	b	2.57(\pm 0.05)	b	11.32(\pm 0.07)	b	1.05(\pm 0.02)	a
	915005	32.55(\pm 0.58)	a	2.80(\pm 0.03)	a	11.61(\pm 0.13)	ab	1.00(\pm 0.01)	a
	1079	32.60(\pm 0.67)	a	2.75(\pm 0.06)	a	11.88(\pm 0.13)	a	1.00(\pm 0.01)	a
	915319	30.99(\pm 0.59)	ab	2.73(\pm 0.04)	ab	11.36(\pm 0.09)	b	1.05(\pm 0.02)	a
	DN2	29.88(\pm 0.82)	b	2.57(\pm 0.05)	b	11.66(\pm 0.15)	ab	1.01(\pm 0.02)	a
20–40	747210	8.81(\pm 0.66)	ab	0.86(\pm 0.06)	ab	10.06(\pm 0.09)	ab	1.22(\pm 0.04)	a
	915005	11.49(\pm 1.83)	ab	1.05(\pm 0.14)	ab	10.76(\pm 0.25)	a	1.22(\pm 0.03)	a
	1079	12.29(\pm 1.64)	a	1.14(\pm 0.13)	a	10.43(\pm 0.36)	ab	1.17(\pm 0.05)	a
	915319	8.79(\pm 1.29)	ab	0.87(\pm 0.10)	ab	9.61(\pm 0.44)	ab	1.25(\pm 0.03)	a
	DN2	7.76(\pm 1.42)	b	0.78(\pm 0.11)	b	9.46(\pm 0.51)	b	1.22(\pm 0.03)	a
40–60	747210	1.05(\pm 0.16)	a	0.23(\pm 0.01)	a	4.54(\pm 0.63)	a	1.28(\pm 0.02)	a
	915005	1.69(\pm 0.27)	a	0.24(\pm 0.01)	a	6.37(\pm 0.80)	a	1.27(\pm 0.02)	a
	1079	1.61(\pm 0.25)	a	0.25(\pm 0.01)	a	6.41(\pm 0.92)	a	1.26(\pm 0.03)	a
	915319	1.46(\pm 0.16)	a	0.24(\pm 0.01)	a	6.03(\pm 0.49)	a	1.27(\pm 0.02)	a
	DN2	1.31(\pm 0.18)	a	0.22(\pm 0.01)	a	5.86(\pm 0.74)	a	1.28(\pm 0.02)	a

SOC concentration: soil organic carbon concentration; Total N concentration: soil total nitrogen concentration; BD: soil bulk density. Different letters indicate significant differences between clones at each depth ($p < 0.05$). Clones are arranged in ascending order of their growth rates.

biomass and the longest fine roots in a study that compared root characteristics between five poplar clones (Al Afas et al., 2008). The increase in fine root production could be related to a higher nutrient demands since clones from this crossbreed had higher leaf N concentrations and lower C/N ratios (branch and stem) than other clones (Pearson et al., 2010). Fine roots have greater root respiration rates than coarse roots (Desrochers et al., 2002; Roumet et al., 2016). On the other hand, Finzi et al. (2015) also found that fine roots produce more exudates than coarser roots, which would enhance the priming effect and further reduce C stocks in the soil (Dijkstra et al., 2006).

For the mid-productive clones that stored more SOC, their roots could be more resistant to the decomposition compared to those of the other clones since their soil C/N ratio was higher in the 20–40 cm soil layer (Table 2). Lower root decomposition rates could be related to higher root C and lignin concentrations and lower root N, hemicellulose and water-soluble compound concentrations (Aulen et al., 2012; Ma et al., 2016; Roumet et al., 2016; Wang et al., 2010; Zhang and Wang, 2015). However, these root traits were not measured in our study and would need to be experimentally determined. The roots of mid-productive clones could have higher recalcitrant compound concentration that requires specific degradation enzymes for decomposition (de Boer et al., 2005; Zak et al., 2006). Wardle (2004) reported that recalcitrant organic compounds contributed more to short-term SOC storage than high quality litter because of their resistance to enzymatic attack.

4.3. Potential of fast-growing plantations to sequester C in the soil

SOC sequestration is influenced by several factors including the abundance of plant-derived inputs, their decomposition rate, and their stabilization through interaction with soil minerals (Mueller et al., 2015). All soil C/N ratios ranged from 6 to 12 in our study, suggesting that OM decomposition rates had reached a very advanced stage (Bui and Henderson, 2013; Fazhu et al., 2015). Fast-growing plantations generally provide high-quality OM rich in labile and low molecular weight compounds that require a low amount of energy for their decomposition (Agren and Bosatta, 1987). Consequently, in a “litter-centered” approach, fast-growing plantations contribute less to SOM stabilization and SOC storage in the short term (Parton et al., 1987; Poirier et al., 2018b; Wardle, 2004). However, recent studies have confirmed that labile and high quality organic compounds are more efficiently consumed by microorganisms and that the microbial biomass and necromass produced are easily stabilized by soil mineral phases (Cotrufo et al., 2013; Lehmann and Kleber, 2015; Schmidt et al., 2011). Poirier et al. (2018a) also found that they promoted the formation of water-stable macroaggregates in the rhizosphere. Fast-growing trees would thus be more conducive to long-term storage of SOC than slow-growing

ones.

Converting cultivated or abandoned agricultural land to short-rotation woody plantations has been widely reported to reverse the process of C loss and increase SOC storage (Arevalo et al., 2011; Garten, 2002; Grigal and Berguson, 1998). For example, SOC stocks of hybrid poplar plantations increased by 13 Mg ha⁻¹ at the 0–50 cm depth after 11 years compared to that of agricultural land and the rate of increase in the SOC was 2 Mg ha⁻¹ year⁻¹ (Arevalo et al., 2011). However, afforested lands can also store less soil carbon than abundant land left to natural succession (Thibault et al., 2022). Fast-growing plantations acted as a soil C source during the initial years of establishment due to low input from tree biomass and litter and due to soil preparation and weed control that could accelerate OM decomposition (Arevalo et al., 2011; Grigal and Berguson, 1998). Hybrid poplar plantations reached pre-plantation levels of soil C only after 7 years in central Alberta, Canada (Arevalo et al., 2011) or 15 years in Minnesota, USA (Grigal and Berguson, 1998). Fast-growing trees could thus require at least 10 to 15 years to be considered as soil C sinks.

Our results showed that our hybrid poplar plantation established on agricultural land in North-Eastern Ontario, Canada, stored up to 95.73 Mg ha⁻¹ to a depth of 60 cm after 14 years. SOC stock in the top 60 cm was lower in our study than in a 9-year-old hybrid poplar plantation (Arevalo et al., 2011). Since both studies have the same previous land use patterns, soil type (Gleysol versus Luvisol), climatic conditions or clone could be the cause of the difference in SOC stocks. However, SOC concentration in the top 20 cm (31 g kg⁻¹ on average), in our study, was higher compared to the finding by Oelbermann and Voroney (2007) in a 13-year-old agroforestry system using hybrid poplar (DN-177: *P. deltoides* × *P. nigra*) in southern Canada (17 g kg⁻¹). Soil type and land use patterns could explain this difference (intensively managed plantations on Gleysol versus agroforestry system on Luvisol). According to Laganier et al. (2010), clay-rich soils have the potential to accumulate more SOC than soils with a lower clay content. Another reason could be the difference in tree density. Indeed, the tree density was higher in our study (816 trees ha⁻¹) compared to the agroforestry system from Oelbermann and Voroney (2007) (133 trees ha⁻¹), which would have increased OM input from litterfall and root turnover. Truax et al. (2018) also found that higher density plantations of poplars led to greater soil carbon stocks after 14 years. In summary, many other factors, such as previous land use patterns, soil type, climatic conditions species or clone and tree density should be taken into consideration for increasing SOC storage using fast-growing plantations.

5. Conclusion

For our fast-growing plantation using hybrid poplars, there was no

significant relationship between tree productivity and SOC stocks. Differences in SOC stocks were mostly observed between clones. Mid-productive clones stored more SOC than the most productive clone, possibly because they had lower decomposition rate of litter inputs and native organic matter. Here, we report a potential trade-off between aboveground productivity and organic matter decomposition rate to increase SOC storage within fast growing plantations. Our results also suggest that tree roots could play a significant role in SOC storage, especially in the deeper soil horizons. Further studies are needed to experimentally determine if significant differences in specific root traits exist among hybrid poplar clones to specify the roles of tree roots in SOC storage. By increasing global timber supplies, fast-growing trees could reduce pressures on natural forests that are important C sinks. Therefore, they could have a significant positive impact on the global C cycle.

CRedit authorship contribution statement

Toky Jeriniaina Rabearison: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Software, Writing – original draft. **Vincent Poirier:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Visualization, Supervision. **Adam Gillespie:** Methodology, Validation, Writing – review & editing, Visualization. **Jérôme Laganière:** Methodology, Validation, Writing – review & editing, Visualization. **Annie DesRochers:** Conceptualization, Validation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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