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Non-additive effects of mixing hybrid poplar and white spruce on aboveground and soil carbon storage in boreal plantations

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ABSTRACT

The use of trees under intensive management is particularly important for rapid fiber production in boreal regions. Mixed-species plantations using species that have complementary ecological niches, such as hybrid poplar and white spruce, potentially can maximize the use of resources and, consequently, increase productivity. In the context of climate change, vegetation and soil carbon sequestration is of a particular interest as part of a possible means of compensating for CO_2 emissions. Since higher productivity leads to higher CO_2 sequestration, the use of mixed-species plantations could improve the ecological service of carbon storage compared to mono-specific plantations. We compared above-ground and soil C storage of nine-year-old mono-specific plantations of white spruce and hybrid poplar with mixed plantations of these two species. Soil carbon was evaluated by separately sampling four soil horizons, while aboveground carbon was assessed from tree biomass estimates using allometric relationships. Mixing white spruce and hybrid poplar exerted a substantial synergistic effect on above-ground and soil carbon storage. This positive effect was due to greater productivity of poplar (47% of biomass increase) and great accumulation of litter in soil surface horizons (52% L-horizon carbon increase) of mixed-species compared to mono-specific plantations. These results imply that in addition to wood production gains by poplar trees, mixed-species plantations of hybrid poplar and white spruce promotes greater carbon sequestration than mono-specific plantations of either hybrid poplar or white spruce, an important aspect of forest ecosystem services.

1. Introduction

In 2010, the total area of planted forest was estimated to cover 264 million hectares worldwide (FAO, 2010). Although they constituted only 7% of global forest cover (FAO, 2010), these plantations were estimated to supplied about 35% of global roundwood needs (Shvidenko et al., 2005). The use of trees under intensive management is particularly important for rapid fiber production in boreal regions of Canada, where growth rates of natural forests are relatively low (Pothier and Savard, 1998). Within this biome, short-rotation forestry has great potential for supporting ecosystem services in (1) valuing abandoned agricultural lands and degraded forests, (2) reducing harvesting pressure on natural forests (FAO, 2010), (3) becoming sustainable sources of wood supplies, and (4) promoting carbon storage (Kelty, 2006). Many researchers have focused upon vegetation and soil carbon sequestration in natural or planted ecosystems, as a possible means of compensating for CO_2 emissions, which is particularly important in the context of climate change (IPCC, 2007). Soil carbon storage could represent from 50% of total carbon storage in tropical forests to 98% in cropland systems; boreal forests have an intermediate level, with soil organic carbon concentrations corresponding to 84% of total carbon storage at the ecosystem level (Bolin et al., 2000). In this context, maximizing the potential for carbon storage by tree plantations becomes an interesting proposition for increasing compensation for or offsetting increasing CO_2 emissions. For example, afforestation of crop fields and pastures of central Saskatchewan with trembling aspen (*Populus tremuloides* Michaux) was shown to have the potential to sequester 30–75 Mg ha^{-1} of carbon over the next 50–100 years (Fitzsimmons et al., 2004). Forest management has traditionally relied upon mono-specific plantations, which are easier to establish, tend and harvest compared to mixed-species plantations. The former have been criticized for having poor ecological characteristics (Lamb et al., 2005;

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Erskine et al., 2006) and greater risks for the spread of diseases that are incurred by fungal pathogens (Burdon, 2001). In contrast, mixedwoods may have many advantages over pure stands such as higher productivity (Man and Lieffers, 1999; Johansson, 2003) and greater resistance to abiotic and biotic stresses, including damage caused by pests or fungal pathogens (McCracken and Dawson, 1997; Burdon, 2001). However, the productivity benefits that are derived from mixed stands depend upon species composition, because such benefits are not consistently observed in studies of mixture effects (Rothe and Binkley, 2001; Piotto, 2008). Mixed-species stands can be more productive than mono-specific stands through two mechanisms: facilitation between species, i.e., one species improves environmental conditions and, thereafter, the growth of another; or niche segregation, where there is divergence in the use of resources between species with different functional traits, which leads to decreased competition and a better efficiency in using local resources (Vandermeer, 1989).

Mixedwood forests of trembling aspen and white spruce (*Picea glauca* [Moench] Voss) are common across boreal Canada. These two species have complementary ecological niches (i.e., they exhibit niche segregation) resulting in maximal use of resources (Kelty, 1992; Man and Lieffers, 1999; Kelty, 2006): white spruce is a slow-growing, superficially rooted and moderate shade-tolerant species, while aspen (like hybrid poplar) is a fast-growing, more deeply rooted and shade-intolerant species. Due to this complementarity, boreal mixedwoods could be more productive than single-species forest ecosystems (Chen and Popadiouk, 2002). Yet this hypothesis has not always been confirmed. In natural forests, some studies have found greater productivity of mixed compared to pure stands (Martin et al., 2005), with a positive effect of aspen (if less than 41% of total stand basal area) on spruce growth in mixtures (Légaré et al., 2004). Others have found negative effects of spruce on aspen productivity (MacPherson et al., 2001), negative effects of aspen on spruce productivity (Kabzems et al., 2007), or no effect of mixed compared to mono-specific stands (Cavard et al., 2010). In plantations, at least one previous study found positive effects of mixing hybrid poplar (*P. maximowiczii* × *balsamifera clone*) and white spruce in intimate mixtures on the growth of the two species (Benomar et al., 2013). Since greater tree productivity leads to greater CO_2 sequestration, the use of mixed species plantations could improve the ecological service of aboveground carbon storage compared to mono-specific plantations. Furthermore, increases in forest productivity can also increase litter production and litterfall (Rothe and Binkley, 2001; Liu et al., 2005), leading to greater accumulation of organic matter on the forest floor (Sayer et al., 2011; Leff et al., 2012), which may result in an increase in soil carbon storage. Soil carbon storage depends upon the balance between C input rates, i.e., senescent organic matter (branches, leaves, and roots), and output rates, i.e., the decomposition of this organic matter. Some studies found a positive effect of mixing litters on decomposition rates; however, like the effects of mixtures on tree productivity, mixture effects on litter decomposition are also largely dependent upon the particular species that are present in the mixture (Gartner and Cardon, 2004; Hättenschwiler et al., 2005). Needle litter of conifers is often acidic, complex in terms of its chemistry, and generally less palatable for soil decomposers compared with the leaf litter shed by broadleaf deciduous species. In boreal mixedwoods, aspen improved litter decomposition relative to spruce through an increase of soil organism abundance, together with an improvement in litter quality and soil physical and chemical properties (Légaré et al., 2005; Laganière et al., 2009). Consequently, aspen forests store less soil carbon than black spruce forests (*Picea mariana* [BSP] Miller), given the faster rates of decomposition processes in the former compared to the latter (Gower et al., 2000; Vance and Chapin, 2001; Laganière et al., 2011).

In tree plantations, studies have generally focused on tree growth and productivity to determine the best management practices that promote higher timber yield, whereas soil carbon storage is largely less thoroughly investigated. This paucity of information contrasts with studies that have been conducted in natural forest environments (Johnson, 1992). In this paper, we compared above-ground and soil carbon storage in nine-year-old mono-specific plantations of white spruce and hybrid poplar *versus* mixed plantations of these two species. For this purpose, we examined hybrid poplar and white spruce growth, together with humus morphology, in the different planted plots. Quantities of soil carbon were estimated by separately sampling four soil horizons, whereas the quantity of aboveground carbon was assessed from tree biomass, which was calculated using allometric relationships.

We hypothesized the following: (i) Based on the low resource quality of spruce needles and slow decomposition rates in natural spruce forests, we expected that carbon storage would be greater in surface soil horizons of mono-specific spruce plantations compared to mono-specific hybrid poplar and mixed plantations. (ii) Due to an increase in productivity, we expected carbon storage in aerial biomass to be higher in mixed plantations compared to mono-specific plantations. (iii) Given a potentially positive effect of mixing species on organic matter decomposition rates compared to mono-specific plots, we expected lower carbon storage within the soil surface horizons (non-additive effect).

2. Materials and methods

2.1. Study area

The study was located in the boreal region of Abitibi-Témiscamingue, Quebec, Canada. Three sites were selected for study: Amos (48°36′N, 78°04′W), Rivière Héva (48°11′N, 78°16′W), and Nédelec (47°45′N, 79°22′W). The Amos site was abandoned farmland with a heavy clay soil that was dominated by grasses and sparse patches of speckled alder (*Alnus incana* [L.] Moench ssp. *rugosa* [Du Roi] R.T. Clausen), willow (*Salix* spp.), and trembling aspen. Rivière Héva was an abandoned farmland site with heavy clay soil, which was also dominated by shrubs, including patches of alder, willow, and aspen. Nédelec had been previously dominated by trembling aspen forest, which was commercially harvested in 2000. In addition to aspen, the main species that were present included white or paper birch (*Betula papyrifera* Marshall) and pin cherry (*Prunus pensylvanica* L.f.), which were growing on soil with a sandy loam texture. Soil type of the three sites ranged from a Brunisol with a Bm-layer to a grey Luvisol with a Bt-layer or Gleysol (Soil Classification Working Group, 1998). Based on a 30-year running climate average (1970–2000), Amos and Rivière Héva annually receive an average of 918 mm year^{-1} (Amos station) and have a mean temperature of 1.2 °C, while Nédelec has mean precipitation of 916 mm year^{-1} and a mean temperature of 1.9 °C (Remigny station, Environment Canada 2014). Site preparation before planting was conducted in 2002. A bulldozer was used to remove tree stumps at Nédelec, while shrubby vegetation at Rivière Héva was removed using a brush shredder mounted on a farm tractor. At Amos, scattered tree stumps and shrub clumps were removed using chains and a farm tractor. Sites were then ploughed to a depth of about 30 cm, followed by disking in spring 2003 to level the soil surface and remove most woody debris (Benomar et al., 2011). The plantations were established in 2003, using one hybrid poplar clone (*Populus maximowiczii* A. Henry × *P. balsamifera* L., clone MB915319), and an improved white spruce family from a provincial seed orchard. These two species were planted in mono-specific plots of 36 trees (6 × 6 trees) with 1 × 1 m spacing, and in mixed species plots, where rows of spruce alternated with rows of poplar, which was