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Land use change effects on ecosystem carbon balance: From agricultural to hybrid poplar plantation

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ABSTRACT

Quantifying the carbon (C) balance of short-rotation woody crops is necessary for validating the C sequestration potential of these systems. We studied the changes in net ecosystem productivity (NEP) and ecosystem C storage 2–4 and 9–11 years after converting an agricultural land (planted to canola, *Brassica napus* L.) to hybrid poplar (*Populus deltoides* × *Populus* × *petrowskyana* var. Walker) plantations in the Parkland region in central Alberta, Canada. The NEP across land uses ranged between 0 and 13 Mg C ha^{-1} year^{-1}, while changes in C storage over two years (2006–2008) ranged between 1 and 7 Mg C ha^{-1} year^{-1} as biomass C and between −1 and 6 Mg C ha^{-1} year^{-1} as soil organic C. When agricultural land was converted to hybrid poplar plantations, soils under hybrid poplar plantations were initially large sources of C losing a total of 8 Mg C ha^{-1}. As cultivation ceased and net primary productivity (and thus litter input) increased, the soil started to become a net C sink by year 2, reaching its pre-plantation level by year 7. At the ecosystem level, hybrid poplar plantations were a source of C in the first 2 years, due to the small contribution of plant biomass and litter relative to soil C loss. Thereafter, the ecosystem acted as a net C sink and reached its pre-plantation level by year 4. We conclude that growing hybrid poplars on rotations longer than 4 years in the study area would create a net C sink and converting agricultural land to fast-growing short-rotation woody crops has the potential for mitigating future climate change.

1. Introduction

Changes in land use affect the cycling and storage of carbon (C) in ecosystems (Guo and Gifford, 2002; Houghton, 1999). The magnitude of change in C storage depends on how physical, chemical, or biological processes are altered over time under different land uses (IPCC, 2000). For example, disturbance caused by land clearing that reduces vegetation cover can increase the loss of soil organic matter through erosion and leaching of dissolved organic C. Such conversions also reduce the potentials for biomass C production (Lal, 2003). In North America, approximately 30–50% of soil C that amounts to 30–40 Mg C ha^{-1} has been lost to the atmosphere and soil organic C (SOC) stocks rapidly declined following conversion from natural to agricultural ecosystems (Lal, 2006). Globally, it has been estimated that changes in land use (from forests to pastures or permanent croplands, and shifting cultivation) released 123 Pg C over the period from 1850 to 1990 (Houghton, 1999), contributing about 18–20% of the total anthropogenic emissions of CO_2 each year (Dumanski, 2004).

On the other hand, afforestation, reforestation, restoration of cultivated, abandoned and marginal agricultural lands can potentially reverse the process of C loss and increase ecosystem C storage (Ross et al., 2002). In this respect, the establishment of large-scale short-rotation woody crop plantations has been advocated as an effective method for sequestering CO_2 and mitigating increased atmospheric CO_2 levels (House et al., 2002), through increasing long-term C storage in woody biomass (Schimel et al., 2001) and in the soil (Garten, 2002), and by providing bioenergy (Tuskan and Walsh, 2001). Converting agricultural land to short-rotation woody crops has been reported to increase SOC by 10–25 Mg C ha^{-1} in 10–15 years (Grigal and Berguson, 1998). However, the net C benefit of these plantations would be site-specific and extensive research and database development would be needed to fully understand the impact of afforestation on ecosystem C balance under different management regimes and in different regions. In particular, it is expected that those plantations would act as a C source during the initial years following establishment due to cultivation (for plantation establishment and weed control) that

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accelerates short-term decomposition of soil organic matter (Grigal and Berguson, 1998).

Therefore, both the rate of C accumulation as well as the turning point when these plantations become a C sink from a C source must be determined. The net balance of C of different processes can be assessed by net ecosystem productivity (NEP) (Randerson et al., 2002), which is the difference between net primary productivity (NPP) and heterotrophic respiration (R_h) from the soil. In addition, the estimation of the sequestration potential of each C pool (e.g., vegetation vs. soil) is important in understanding the dynamics of terrestrial C sinks. The objectives of this study were: (i) to determine the changes in ecosystem C production and storage when a previously agricultural land was converted to hybrid poplar plantations, and (ii) to examine the dynamics of C source-sink relationships in the developing plantation systems to determine the turning point when these plantations become a C sink from a C source.

2. Materials and methods

2.1. Study site

This study was conducted near Linaria (54°12′ N, 114°8′ W), approximately 25 km west of Westlock, in central Alberta, Canada. The study area has a continental climate, with cold winters and warm summers providing a growing season of approximately 180–185 days between May and November (AAFRD, 2003). Climate normals for the study area, based on 12 years of data (1993–2005) collected at a nearby weather station (Environment Canada, 2005), show that the area has a mean annual temperature of 3 °C (mean temperature was 13 °C during the growing season between April to October and −8 °C for the rest of the year) and mean annual precipitation of 463 mm (350 mm of which falls as rain from April to October and 113 mm as snow).

We used a comparative mensurative experimental design (Hulbert, 1984) to compare two land use treatments: agricultural and hybrid poplar plantation systems. The sites were adjacent to each other within an area of 4 km^2 and the soils were developed on the same parent material and are classified as a Dark Gray Luvisol (Agriculture and Agri-Food Canada, 2005). All the study sites (90 ha) were historically under one land-use type, i.e., a native aspen forest (*Populus tremuloides* Michx.), before a greater portion (55 ha) of the land was cleared for agriculture in the 1930s (Herb Smerychynski, 2006, personal communication); and leaving approximately 3 ha of forest land intact. Under agricultural land use, the landowners practiced conventional tillage and added fertilizers for cereal and oilseed crop production (wheat, barley, and canola). Fertilization was usually at 124, 34, 25, and 11 kg ha^{-1} $year^{-1}$ for N, P, K and S, respectively. In the spring of 1998, Millar Western Products Ltd. established a hybrid poplar plantation (*Populus deltoides* × *Populus* × *petrowskyana* cv. Walker) in a small portion (<1 ha) of the agricultural land as part of the company's hybrid poplar test program. In 2004, another portion (20 ha) of the agricultural land was established with hybrid poplar of the same clone by the Canadian Forest Service, as part of the Forest 2020 Plantation Demonstration Assessment Initiative Program of the federal government. Because the plantations originated from the same land use type, on the same soil type, and due to their adjacency to one another, a space-for-time substitution (chronosequence) was used to determine land use change effects from agricultural to hybrid poplar plantation on ecosystem C balance.

Three sampling plots (20 m × 20 m each) were set up in (i) an agricultural field (AG), and (ii) in a young (2 years old in 2006) and old (9 years old in 2006) hybrid poplar plantations, abbreviated as YHP and OHP, respectively. Details of the land use sites including soil physical and chemical properties are given by Arevalo et al. (2009).

2.2. Net primary productivity

Net primary productivity is the amount of biomass produced per unit area per year. In the hybrid poplar plantations, NPP was calculated using the following equation:

$$\mathrm{NPP} = \Delta B + D \quad (1)$$

where, ΔB – the change in the sum of plant aboveground woody biomass (ΔB_{ab}) and coarse roots (ΔB_{cr}) over a period of a year and D – detritus which is the sum of the litterfall, understory biomass (L), and fine root biomass (B_{fr}) produced during the year.

Diameter at breast height (DBH) and height of all trees taller than 1.3 m in each experimental plot were measured on July 27, 2006 and again on July 28, 2008. Above (stem and branches) and belowground (coarse root) biomass was calculated using published allometric equations for hybrid poplars (Ballard et al., 2000; Dickmann et al., 2001; Fang et al., 2007; Wullschleger et al., 2005). The ΔB was the difference in biomass between the two measurements divided by the number of years.

Leaf litter production in the plantations was computed using allometric equations with DBH and tree height as independent variables (Fang et al., 2007). Because of the deciduous nature of these stands, foliage produced in each measurement year was assumed to have returned to the soil as litterfall. Coarse woody debris was not present in any of the sites and therefore was not considered in the calculations. Except in the YHP where the weed control practice was effective and no weed biomass was quantified, aboveground biomass of the understory vegetation at the OHP was measured using three randomly located quadrants (1 m × 1 m) per plot. Understory vegetation were measured on July 27, 2006 and July 28, 2008, when plant biomass peaked. All vegetation was removed from each clip plot, oven-dried at 65 °C until constant weight and weighed.

Fine root production was determined using the maximum–minimum biomass method (Vogt et al., 1998). Fine root biomass was determined using soil core samples collected from each plot three times in each of the two growing seasons (June, August, and October in 2006 and 2008). At each sampling, three 152 cm^3 soil cores were taken to 30 cm depth. Core samples were immediately stored at 2 °C until further processing. Fine roots (<2 mm) were recovered by soaking the soil samples in water and gently washing over two sets of sieves with openings of 2.0 and 0.5 mm, respectively. Fine roots that passed through the 2 mm and retained on top of the 0.5 mm sieve were hand-picked while root material that passed through the 0.5 mm sieve was discarded as such material was impossible to recover. Recovered fine roots were oven-dried at 65 °C for 48 h and weighed. Fine root biomass production for each year was then calculated by taking the difference between October and June fine root biomass values on the assumption they were at maximum and minimum at those two sampling occasions, respectively.

For the agricultural site, NPP was calculated as described below. Total crop biomass, crop residue (canola stubble left on the ground after harvest), and roots were measured each sampling year. Total crop biomass were measured on July of 2006 and 2008; crop residue on September of 2006 and 2008; and roots in June, August, and October in 2006 and 2008. Harvested crop biomass (total crop biomass but not including crop residue) was removed from the site while crop residue and roots were incorporated into the soil after each growing season. Due to the annual nature of biomass production in the agricultural site, we assumed that litter from crop residue and roots have returned to the soil the same year they were