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# Carbon sequestration and water use of a young hybrid poplar plantation in north-central Alberta

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ABSTRACT

Hybrid poplar (HP) is an important fast-growing crop with the potential to provide a reliable supply of biomass for the pulp and bioenergy industries while also sequestering carbon (C) in the soil. We used the eddy-covariance technique to measure $CO_2$, water vapor and sensible heat fluxes above a three-year-old HP plantation on high productivity land near St Albert, Alberta. Measurements showed that the annual C balance of the plantation shifted from a C source of about 1.54 Mg C $ha^{-1}$ $y^{-1}$ in the 2nd year (2010) to a C sink of 0.80 Mg C $ha^{-1}$ $y^{-1}$ in the 3rd year (2011). Water use or evapotranspiration ($E$) for 1 June – 31 October increased from 272 mm in 2010 to 321 mm in 2011, and exceeded the respective values of total precipitation of 251 mm and 298 mm for the same period. Annual $E$ in 2010 of 364 mm was less than annual precipitation of 398 mm. In 2011, annual $E$ (442 mm) exceeded annual $P$ (411 mm) by 31 mm; it also exceeded the annual plantation water use $E_{wb}$, estimated using a water balance method assuming no drainage from the root zone, by 40 mm. However, both courses of cumulative $E$ and $E_{wb}$ closely followed cumulative $P$. Monthly $E$ increased with increasing net radiation and gross primary productivity. Growing season mean albedo increased from 0.16 in 2010 to 0.21 in 2011 and was consistent with the increase in broadband NDVI. Values of albedo during winter months (November–April) exceeded 0.80. The results suggested that as the plantation grows, growing season albedo, annual C sequestration, and annual water use will increase with the possibility that the latter may exceed annual precipitation. This emphasizes the need to study the long-term sustainability of HP plantations in relation to annual $P$ and its temporal distribution, especially when HP plantations will likely be established on large contiguous areas to supply biomass feedstock for the expanding pulp and bioenergy industries in Western Canada.



## 1. Introduction

The forest industry in Canada is under increasing pressure to secure alternative wood fibre sources as a result of impending shortages of wood from natural forests due to current unfavorable age-class distributions, changes in acceptable forest management practices, emphasis on the preservation of old-growth forests, and losses of forest due to oil-sands and

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mining development and industrial expansion. For example, in Alberta alone, about 5000 $km^2$ of boreal forestland has been lost to oil and gas exploration, and to coal and oil-sands extraction [1,2] with possibly large increases in such activities in recent years. Furthermore, with projected increases in mill production capacity and development pressures on forestland, shortages of wood fibre are expected in the future [3]. In the Prairie Provinces, woody biomass from short-rotation hybrid poplar (HP) plantations has great potential for a high fibre base in the pulp industry [4,5], biomass for bioenergy [6], long-term C sequestration in woody biomass and soil organic matter [7], and forest products [8].

Biomass production using fast growing HP plantations depends on the availability of water and nutrients and the management regime. Especially attractive is the idea of establishing HP plantations on waste disposal sites [9] and agriculturally marginal lands [10], where additional financial flow from biomass production for energy could benefit rural landowners. HP growth and biomass yield vary significantly as a function of site characteristics, climatic conditions, and genotype [10–13]. In high-density HP established on both fertile and infertile soils in northern Wisconsin, Hansen et al. [14] found that with irrigation and fertilization, mean annual increment (MAI) of aboveground tree biomass was 6.7 Mg DM (dry matter) $ha^{-1}\ y^{-1}$ at 5 years of age. In a review of maximum biomass productivity of hardwood stands including *Populus* spp., Cannell and Smith [15] reported MAI of aboveground tree biomass of 10–12 Mg DM $ha^{-1}\ y^{-1}$ for both 4–5 and 11–26 year-old plantations. Heilman and Fu-Guang [16], in a study conducted on 6 clones in the Puyallup River valley, Washington, found that MAI of aboveground tree biomass for 4-year-old HP increased from 15 to 27 Mg DM $ha^{-1}\ y^{-1}$ in control plots to 19–31 Mg DM $ha^{-1}\ y^{-1}$ in N-fertilized plots. Furthermore, fast-growing HP allows sequestration of C in long-term storage pools, i.e., wood biomass [17] and the soil [18]. Land use change from agriculture or native forest to HP plantations results in decreased soil C stocks during the first 2–6 years after which they increase [18,19]. Using the eddy-covariance (EC) technique, Cai et al. [20] showed that the annual C balance of HP plantations on marginal (Class 3) agricultural land [21], in Alberta, Canada, shifted from a strong C source of 3.3 Mg C $ha^{-1}\ y^{-1}$ in the 1st year to C-neutral in the 5th year.

Fast-growing HP plantations are known to have high water requirements [22,23] with their potential growth highly dependent on the amount of available soil water [24,25]. EC measurements of water use on marginal agricultural land in Alberta have shown that annual water use (i.e., evapotranspiration, $E$ ) varied from 281 mm for a 1-year-old HP plantation to 323 mm in the 4th year [20]. In comparison, mean annual water use of a 12-year-old HP plantation in Italy that received 140 kg N $ha^{-1}$ at planting, also using the EC technique, was 450 mm [26]. Conversion from arable land to short rotation HP plantations in the Netherlands resulted in a 23% reduction of drainage [27]. Perry et al. [28], using measurements and modeling, found that conversion of annual croplands to HP could reduce the annual regional water yield as well as the annual peak flows in streams feeding the Red River. With an extensive area being converted to HP plantations in the Prairie Provinces, it is expected that growth and sustainability of HP may be compromised due to limited precipitation with possible adverse effects on the regional water balance [29], e.g., extensive plantations will make less water available to neighboring crops or grazing lands and/or will reduce ground water storage and stream flow. The hydrologic effects of afforesting large areas of land with HP on the farming landscape in Western Canada have not been investigated. The continuing dieback and reduced growth of aspen in Western Canada in the Aspen Parkland ecoregion, mainly due to water deficit [30,31] is an analog of possible future changes with a steadily increasing area of HP plantations. Thus the key to ecologically, environmentally and economically sustainable HP is the availability of adequate water and nutrients to meet the requirements of increased growth and $E$. The latter is expected to increase with increasing vapor pressure deficits as a result of increasing air temperature and reduced summer rainfall as forecasted by climate models. There is need to study the long-term sustainability of HP plantations in relation to annual total precipitation and its temporal distribution, especially when HP plantations will likely be established on large contiguous areas to supply biomass feedstock for expanding pulp and bioenergy industries in the Canadian Prairies. To understand the effects of different soil and climatic conditions on the growth and water use efficiency (WUE), and to develop models for forecasting sustainability of rainfed HP plantations in Western Canada, we have begun making measurements of ecosystem-level fluxes of $CO_2$ and water vapor using the EC technique. The objective of this paper is to determine the C, water and energy fluxes, and their environmental controls, in a 3-year-old HP plantation growing on fertile, Class 1 land, and assess the sustainability of HP plantations in relation to the supply of water by precipitation in north-central Alberta.

## 2. Materials and methods

### 2.1. *Site and instrumentation description*

The HP plantation is located at 53° 42′ 27.8″ N, 113° 37′ 46.9″ W on level ground near St Albert near Edmonton, Alberta, Canada on a clay loam Chernozem, Class 1 (high productivity) soil [21]. A 20-ha area was planted in June–July 2009 with HP (*Populus deltoides* × *Populus petrowskyana*) rooted cuttings of mainly *Walker* cultivar at 2.5 m × 2.5 m spacing with an additional 10 ha planted on the south edge during May–June 2010. Site preparation before planting included two cultivations: one deep (25–30 cm) and one shallow (10 cm). Ecosystem-scale $CO_2$, water vapor and sensible heat flux measurements using the EC technique and climate measurements began in June 2010. The EC sensors were initially mounted on a tripod at a height of 1.5 m above the ground. The EC-measurement height was raised, in response to increasing tree height, to 2.5 m in Sep 2010, and to 4.5 m in Sep 2011 when the tripod was replaced with a scaffold tower (2.1 m long by 1.5 m wide and 4 m high). Winds were generally from the south-west and flux footprint analysis [32] showed that during the growing season the upwind distances from the flux tower to the 80% cumulative flux contour were typically within 200 m and 300 m during the daytime and nighttime, respectively. EC instrumentation consisted of a 3-axis sonic