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Photosynthesis and aboveground carbon allocation of two co-occurring poplar species in an urban brownfield☆

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ABSTRACT

Phytoremediation, a technique used to reclaim heavy metal-contaminated soils, requires an understanding of plant physiological responses to heavy metals. However, the majority of studies documenting heavy metal impact on plant functioning have been performed in laboratory or greenhouse settings. We predicted that increased soil heavy metal concentrations reduce photosynthesis and biomass production in trees growing in metal contaminated soil in a naturally re-vegetated urban brownfield. Leaf gas exchange, leaf carbon and nitrogen concentration, and tree biomass were recorded and compared for *Populus deltoides* and *Populus tremuloides* growing in an urban brownfield. The CO_2 compensation point (CCP) differed significantly between soil metal concentrations and species, with *P. deltoides* displaying a greater CCP and *P. tremuloides* displaying a lower CCP as soil metal concentration increased, despite no changes in dark respiration for either species. In terms of biomass, only total branch weight (TBW) and leaf area (LA) differed significantly between soil metal concentrations, though the difference was largely attributable to variation in diameter at breast height (DBH). Furthermore, TBW and LA values for *P. deltoides* did not decrease with increasing soil metal concentration. Soil metal concentration, thus, had minimal effect on the relationship between tree age and DBH, and no effect on relationships of tree age and height or LA, respectively. Significant differences between soil metal concentrations and species were found for $\delta^{15}N$ (isotopic nitrogen ratio) while leaf nitrogen content (% N) also differed significantly between species. Long-term water use efficiency derived from carbon isotope analysis ($iWUE_{isotope}$) differed significantly between trees grown on different soil metal concentrations and a significant species-metal concentration interaction was detected indicating that the two study species responded differentially to the soil metal concentrations. Specifically, *P. tremuloides* enhanced while *P. deltoides* reduced long-term $iWUE_{isotope}$ as soil metal concentration increased, further emphasizing the importance of species and possible genotype selection for phytoremediation.

1. Introduction

Numerous areas across the globe are suffering from heavy metal contamination (Lone et al., 2008; McGrath et al., 2001; Meers et al., 2010). Heavy metals pose a serious threat due to their non-biodegradable nature, difficulty of removal, health risks, and buildup in water and soils (Giller et al., 1998; Lone et al., 2008; Mendola et al., 2002). In the United States, there are over 450,000 brownfields, and nearly 80% of Superfund sites and over 50 million cubic meters of soil are contaminated with heavy metals (Dermont et al., 2008; EPA, 2012). It has been estimated that brownfields in the U.S. alone account for the loss of more than 205,000 ha of valuable land that could be used for agriculture, pasture, or forests (Lone et al., 2008). As such, phytoremediation has become widely recognized as a cost-effective, efficient, eco-friendly, and *in situ* applicable method for remediating metal-contaminated soils (Ali et al., 2013; Saier and Trevors, 2010; Vithanage et al., 2012; Wang and Jia, 2010). Species with traits that include fast growth, extensive root systems, and large biomass production have become a

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focus of many phytoremediation studies (Jabeen et al., 2009; Pulford and Watson, 2003; Seth, 2012). Among these plants, members of the genus, *Populus*, are known to comprise a large number of species that are able to grow in metal-contaminated soils (Wang and Jia, 2010).

Many studies on the effects of heavy metals on plant function have been carried out in laboratory or greenhouse settings (Ali et al., 2013; Dos Santos Utmazian et al., 2007; Giachetti and Sebastiani, 2006; Hermle et al., 2006, 2007; Robinson et al., 2007), which, while being effective in controlling environmental variables and isolating cause and effect, do not reflect field conditions and included one year old seedlings to 6 year old trees, hydroponic pot studies and chambered field studies but not established trees in a naturally assembled brownfield.

Studies that have examined the impact of heavy metals on many plant species have found negative effects on photosynthesis and biomass production. Leaf damage, alterations in plant cell structure, and damage to both photosynthetic and water-conducting tissues have been reported in plants dealing with heavy metal contamination (Baryla et al., 2001; Hermle et al., 2007). In response to treatments with copper (Cu), nickel (Ni), and cadmium (Cd), *Populus deltoides* and *Populus euramericana* undergo oxidative stress, leading to damaged chlorophyll molecules followed by reductions in photosynthetic capacity (Trudić et al., 2012). Young trees of *Populus x euramericana* suffered from reduced foliage, impaired gas exchange, and decreased photosynthesis rates in response to zinc (Zn) treatments (Di Baccio et al., 2003). Young trees of *Populus tremula* experienced decreases in transpiration, diameter growth, foliage area, fine root biomass, aboveground biomass, and leaf area, resulting in lower photosynthetic ability when grown with topsoil treated with Cu, Zn, Cd, and lead (Pb) (Hermle et al., 2006; Menon et al., 2007). When grown in soils treated with Cd, Zn, and Cu, two-year-old seedlings of *Populus canadensis* only reached 75% of their biomass production compared to individuals of the same species and age growing in untreated soil (Wang and Jia, 2010). Mature trees of *Betula populifolia* displayed reduced productivity when growing in soils with higher Zn levels (Gallagher et al., 2008a). Mature trees of *P. deltoides* did not significantly differ in terms of photosynthetic functioning between low and high soil metal concentrations, though it was found that trees of *P. deltoides* that were of similar size, tended to be younger when growing on soils with lesser metal contamination (Renninger et al., 2013). Older trees may simply have greater ability to tolerate heavy metals due to their larger size, which conveys greater number of water- and nutrient-conducting, as well as photosynthetic tissues, which may enhance the ability to offset negative impacts of heavy metals. In addition, the established trees may be able to cope better with heavy metal contamination, because their roots explore deeper soil volumes with less contamination, there may be less plant available heavy metals due to complexation with organic matter, confining heavy metals in foliage that gets discarded by the end of the season, other elements that ameliorate damaging effects or the harmful heavy metals are translocated throughout the soil volume (Nocito et al., 2011; Qian et al., 2012; Shen et al., 2016).

The purpose of this study is to examine and compare the effects of heavy metals on photosynthesis and aboveground biomass production in *Populus deltoides* W. Bartram ex Marshall (USDA, 2015a) and *Populus tremuloides* Michx (USDA, 2015b). growing in a naturally re-vegetated brownfield in New Jersey, which contains a persisting soil metal contamination (Evans et al., 2015; Gallagher et al., 2008a, b; Hagmann et al., 2015). Here, it is predicted that *P. deltoides* and *P. tremuloides* will exhibit a higher photosynthetic capacity in sites containing lower soil metal contamination compared to sites with higher soil metal contamination. As a result, productivity for both species is expected to be higher in sites with lower soil metal contamination. Trees of both species growing in highly metal-contaminated soils are expected to have higher leaf dark respiration compared to trees growing in lesser metal-contaminated soils because more energy is required in order to maintain leaf structural and photosynthetic integrity in a heavy metal soil environment (Hermle et al., 2007). Similarly, transpiration is expected to be lower for trees in sites with higher soil metal contamination in order to tolerate metal-induced water stress (Hermle et al., 2007; Lamoreaux and Chaney, 1978; Schlegel et al., 1987). Photosynthetic and intrinsic water use efficiency should then be higher for trees growing in sites of higher soil metal contamination due to lower transpiration or lower stomatal conductance, respectively (Gallagher et al., 2008a; Renninger et al., 2013).

2. Materials and methods

2.1. Study site and species selection

The study was carried out in Liberty State Park (LSP), which is located in Jersey City, New Jersey, U.S.A. Liberty State Park originally existed as an intertidal mudflat and salt marsh before undergoing a land use change and being filled with waste from New York City in order to be made usable as a rail yard for the Central Railroad of New Jersey (CRRNJ) (Gallagher et al., 2008b). The area was used by the CRRNJ until 1967, leaving the area abandoned (NJ Department of Environmental Protection (2009)). Later, the area was purchased with government funds and upon the completion of cleanup efforts (http://www.nan.usace.army.mil/Portals/37/docs/civilworks/projects/nj/ecor/HRELiberty/htrw.pdf), the area was officially opened as a public park in 1976 (NJ Department of Environmental Protection (2009)). The LSP consists of approximately 490 ha, and while the park has been largely restored, a 102 ha area still exists that is fenced off and closed to public access (NJDEP, 2002; Renninger et al., 2013) because of its classification as a brownfield due to soil heavy metal contamination (Gallagher et al., 2008a). Specifically, the area has been found to be contaminated with arsenic (As) from 9 to 31 $\mu g\ g^{-1}$, Cr ranging from 18 to 96 $\mu g\ g^{-1}$, Cu ranging from 52 to 76 $\mu g\ g^{-1}$, Pb ranging from 177 to 414 $\mu g\ g^{-1}$, vanadium (V) in the range of 21–137 $\mu g\ g^{-1}$, and Zn ranging from 69 to 140 $\mu g\ g^{-1}$ (Hagmann et al., 2015), of which soil concentrations of As, Cr, Pb, V, and Zn are considered to be above normal for New Jersey soils (Gallagher et al., 2008a; Sanders, 2003). Previous soil sampling done in 2005 indicated that soil contamination was highly heterogeneous across the area (Gallagher et al., 2008a) and remains so to this day (Hagmann et al., 2015). Despite the presence of metal-contaminated soils, the area has been naturally re-vegetated, with *Betula populifolia* Marsh. (35%), *Populus deltoides* W. Bartram ex Marshall (16%), and *Populus tremuloides* Michx. (14%) representing the dominant species in the hardwood areas (Evans et al., 2015; Gallagher et al., 2008a; Hagmann et al., 2015; Renninger et al., 2013).

Within this 102 ha fenced off area, six sites were chosen for this study, each representing areas of high, medium, or low soil metal contamination based on the composite soil metal concentration present using the composite soil metal concentration map and site designations in Gallagher et al. (2008a). Details on the heterogeneity of metal concentrations and specifically which metals have higher or lower concentrations at the different sites have been previously reported in Gallagher et al (Gallagher et al., 2008a, b; Renninger et al., 2013). and more recently in Hagmann et al. (2015) and Qian et al. (2012). Sites 41 and 48 were selected as areas of low soil metal concentrations (LM) and sites 14/16 and 25 as areas of high soil metal concentrations (HM) in order to examine heavy metal effects on gas exchange and leaf nutrient