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Tree-ring width and $\delta^{13}C$ records of industrial stress and recovery in Pennsylvania and New Jersey forests: Implications for CO_2 uptake by temperate forests

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ABSTRACT

We present dendrochronological records of tree-ring width and $\delta^{13}C$ values for representative living trees (ages of 70 to 230 years) in Pennsylvania and New Jersey to investigate the ecological responses to industrial pollution and recent management and their effects on carbon storage in the temperate forests. Chestnut oak, red oak and cedar trees consistently show elevated $\delta^{13}C$ levels (1.3 to 4.1‰ higher than unpolluted normal values) during the period of intense pollution from ~1900 to ~1970, indicating significant industrially induced physiological stress on the trees. Since ~1970, oak and cedar trees have shown remarkable increase in growth rates and rapid decrease of 0.6 to 2.5‰ in $\delta^{13}C$ values, indicating the recovery of trees corresponding to the implementation of the Clean Air Act in the early 1970s. The growth enhancement since 1970 has resulted in an increase in biomass of ~26% in cedar trees and ~66% in oak trees, suggesting that air-cleaning efforts have made a significant contribution to CO_2 uptake by the temperate forests, at least in the northeastern USA.

1. Introduction

Industrial emission in the past 150 years has caused tremendous increase in atmospheric CO_2, NO_x, SO_2 and O_3. In the USA, the levels of these pollutants have in general shown decrease after implementation of federal regulation of industrial emissions (e.g., in 1970 for SO_2 and in 1980 for NO_x), such as by the US Environmental Protection Agency (USEPA). Understanding of the responses of terrestrial ecosystems to elevated air pollutant levels, and later air-cleaning efforts, is crucial in modeling the terrestrial carbon (C) budget and plotting future management. Thus far, most of previous studies have focused on investigation of the effect of elevated pollutants (e.g., Darall, 1989; Strand, 1993). The effect of air-cleaning efforts on the recovery of terrestrial ecosystems has received far less attention.

A number of studies in the laboratory and field, including on natural forests, have revealed that the response of plants to elevated levels of individual industrial pollutants can be two-fold, involving (1) enhanced growth as a result of CO_2 fertilization (e.g., Ainsworth and Long, 2005; Curtis and Wang, 1998; DeLucia et al., 1999; Ellsworth, 1999; Norby et al., 1999; Nowak et al., 2004) or of elevated atmospheric N deposition in N-limited regions (e.g., LeBauer and Treseder, 2008; Magill et al., 1997; Magnani et al., 2007; Thomas et al., 2010); and (2) reduced assimilation of CO_2 at high levels of O_3 (e.g., Chappelka and Samuelson, 1998; Darall, 1989; McLaughlin and Downing, 1995; Pye, 1988; Tjoelker et al., 1995) or SO_2 (e.g., Darall, 1989; Sakata and Suzuki, 2000; Savard et al., 2002, 2004; Strand, 1993) due to their phytotoxicity.

Fewer studies have examined the interactive effects of these pollutants. Experimental studies show that O_3 impacts can be ameliorated by elevated CO_2 levels (Volin et al., 1998; Karnosky et al., 2003). Modeling efforts consistently indicate that the enhanced CO_2 uptake in response to CO_2 fertilization and N deposition can be cancelled out by the impact of O_3, apparently resulting in the growth estimate for the case of combined pollutant effects similar to that of no disturbance (Felzer et al., 2007; Ollinger et al., 2002). However, the effect of SO_2 (one of the major industrial pollutants) has not been integrated in experimental and modeling studies, impeding full understanding of industrial impacts on terrestrial ecosystems. A detailed dendrogeochemical study on the natural forests along an SO_2 gradient from a smelter in Québec (Canada) shows that SO_2 imposed great physiological stress on boreal trees, even on those trees more than 100 km away from the SO_2 point source (Savard et al., 2002, 2004). Because SO_2 is one of the major pollutants released by industrial activities, its impact may play an important role in the aggregate effect of all important pollutants on terrestrial ecological CO_2 uptake. Given that the positive effect by CO_2 and N fertilization and the negative effect by O_3 are roughly equivalent in magnitude, if no other factor is considered, the aggregate industrial effect would strongly depend

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on the SO_2 level. This has seemingly been demonstrated by the relationship between industrial SO_2 emission and the decline of fir forests in Japan (Sakata and Suzuki, 2000).

The aggregate industrial impact and the effect of air-cleaning efforts (if any) on forests can be probed by direct investigation of environment-sensitive proxies from old living trees that live through these periods. Tree-ring width and C isotope compositions are commonly used to detect the environmental stresses. Unlike tree-ring width that may be affected by age-related exponential decrease, obscuring environmental signals, C isotope compositions of tree wood are less affected by this age-related phenomenon and can provide a more sensitive record of environmental stresses, particularly anthropogenic environmental changes over the last 150 years (Freyer and Belacy, 1983). Trees can biologically discriminate C isotopes (preferentially using ^{12}C) when they assimilate CO_2 from the atmosphere and yield ^{13}C-depletion tree woods. The C isotope fractionation between tree wood and atmospheric CO_2 can be expressed as (Farquhar et al., 1982):

$$\Delta^{13}C = \delta^{13}C_{\mathrm{tree}} - \delta^{13}C_{\mathrm{air}} \approx a + (a-b)c_i / c_a, \tag{1}$$

where $\delta^{13}C$ is defined as:

$$\delta^{13}C = \frac{\left({}^{13}C/{}^{12}C\right)_{\mathrm{sample}}}{\left({}^{13}C/{}^{12}C\right)_{\mathrm{standard}}} - 1 \tag{2}$$

and a represents the fractionation caused by CO_2 diffusion through leaf stomata, b represents the fractionation caused by the ribulose-biphosphate carboxylase-oxygenase (Rubisco), and c_i/c_a represents the ratio between leaf intercellular and ambient atmospheric CO_2 concentrations. Industrial emissions of toxins (e.g., SO_2 and O_3) can affect enzyme activity (Strand, 1993) and reduce a tree's ability to discriminate between isotopes, resulting in elevated $\delta^{13}C$ values.

In this study, we investigated tree-ring width and the $\delta^{13}C$ series of trees, of ages of up to >200 years, from natural forests in Pennsylvania (PA) and New Jersey (NJ), USA. This region, located downwind of the Ohio Valley (the industrial centre of the USA), has been heavily polluted. Industrial emissions (particularly of SO_2) increased significantly from ~1900 to 1970 (hereafter referred as the *pollution period*), due to the operation of smelters, and reduced rapidly after 1970 (hereafter as the *recovery period*) as a result of the regulation mandated by the Clean Air Act. Investigation of ecological responses to these industry-related environmental changes may contribute to the understanding of ecological CO_2 uptake over the last 150 years and assist in projecting the terrestrial C sink in the future.

2. Study sites and analytical methods

2.1. Study sites and local industry history

Pennsylvania and New Jersey are among the most heavily industrialized areas in the northeastern USA (Fig. 1), where increasing emission of pollutants from industrial plants since ~1850 caused severe environmental problems. Since 1970, with the implementation of environmental regulation, the emission of SO_2 and heavy metals showed sharp decrease. Available data acquired since 1980 show that the ground-level O_3 has only slightly decreased (USEPA, 2004). Although there were more minor and transient industrial activities, two large industrial plants had the greatest environmental impact in this area over the last 100 years: the smelters of New Jersey Zinc Company located in Palmerton, Pennsylvania (1898-1980), and plants of Bethlehem Steel located in Bethlehem, Pennsylvania (1899-1995). Industrial activities for these localities are briefly described below.

2.1.1. Palmerton, Pennsylvania

The Palmerton valley is bounded by Blue Mountain to the south and Stony Ridge to the north, and is cut through by the Lehigh River to the west of the town of Palmerton. This topography strongly affects the local patterns of atmospheric circulation, temperature and precipitation. The atmospheric circulation pattern is highly inconsistent, mostly out of the north to the west and more frequently in the winter while intermittent episodes of low wind speed and stagnant air in the summer. The mean annual temperature is 10.4 °C with mean low of 4.6 °C and mean high of 16.1 °C. The mean annual precipitation is 1068.8 mm, which is mostly precipitated during the summer growing season.

The tree coring site is located in the Lehigh Gap Wildlife Refuge at the west bank of Lehigh River, within a few kilometers leeward of the west plant of the now-defunct zinc smelters of New Jersey Zinc Company, which is one of the few localities where trees are available in that area (also see summary by WEF, 2000). The windward side has been severely degraded and is often referred to as a barren wasteland. The greatest environmental damage to the mountain

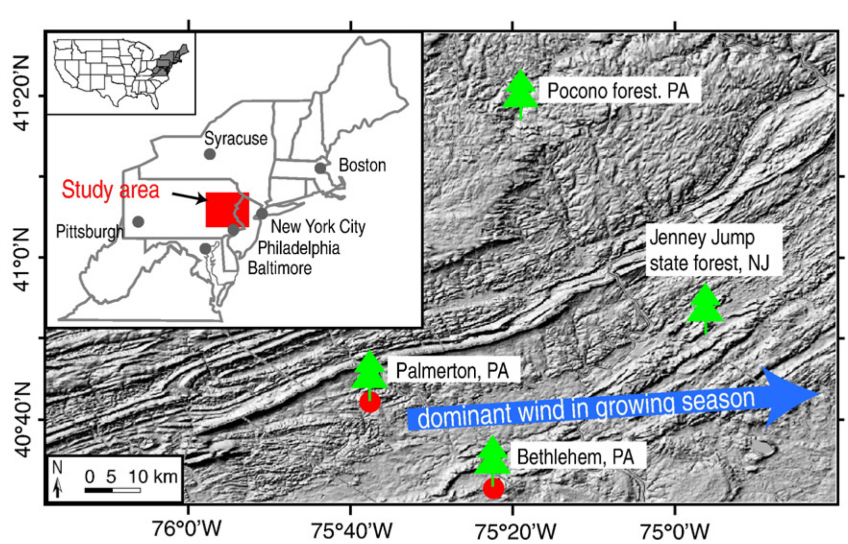

Fig. 1. Digital elevation model showing the study localities in Pennsylvania and New Jersey. Two major local industrial plants are marked by solid circles. Coring sites are marked by tree-like symbols. The dominant wind direction in the growing season is also shown by an arrow. Insets indicate the location of the study area as well as the major industrial centers in the northeastern United States.