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Effects of metal-contaminated soil on the performance of young trees growing in model ecosystems under field conditions

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Four tree species had different responses to metal treatments.

Abstract

Young *Populus tremula*, *Salix viminalis*, *Betula pendula* and *Picea abies* trees were grown together in large open-top chambers. The treatments were: without or with (Cu/Zn/Cd/Pb = 640/3000/10/90 mg kg^{-1}) metal contamination in the topsoil, irrigation pH 3.5 or 5.5, and acidic or calcareous subsoil. Growth, metal allocation to foliage and wood, as well as leaf gas exchange were measured. Biomass was reduced in *P. tremula* and *B. pendula* by the metal-contaminated topsoil relative to uncontaminated topsoil, whereas in *P. tremula* photosynthesis and transpiration were decreased. These effects were related to the elevated foliar Zn accumulation in *P. tremula*. *S. viminalis* showed a significant reduction in growth and an increased Zn and Cd accumulation on acidic vs. calcareous subsoil. Acidic irrigation produced only a few significant effects. *P. abies* showed the lowest metal uptake and no growth response to metal contamination.

Keywords: Soil pollution; Metal allocation; Biomass production; Photosynthesis; *Populus tremula*; *Salix viminalis*; *Betula pendula*; *Picea abies*

1. Introduction

Metals, such as cadmium (Cd), copper (Cu) and zinc (Zn), are primarily of geogenic origin in forest soils, but locally significant inputs from anthropogenic sources (via atmospheric deposition) also have been found (Hesske et al., 1998). For example, at some sites that are in the vicinity of Zürich and that are exposed to air pollution, metal concentrations in the uppermost centimetres of forest soils were two to three times higher than at comparable sites not exposed to air pollution (Schindler et al., 1991). Fortunately, the great majority of Swiss forest soils do not exceed the Swiss recommended limit for HNO_3-extractable metal concentrations (Pb: 50 mg kg^{-1}; Cu: 50 mg kg^{-1}; Cd: 0.8 mg kg^{-1}; Zn: 200 mg kg^{-1}; BUWAL, 1993). However, many forest soils have a rather low pH, whereas agricultural soils are kept mostly around neutral pH due to fertilisation and liming. Under such conditions the bioavailability of Cd, Cu, Pb and Zn is generally low (Streit and Stumm, 1993). Dissolved or soluble metal concentrations, in particular those of Cd and Zn, are often much higher in forests than in adjoining agricultural soils (Römkens and Salomons, 1998). Consequently these metals also become more available for accumulation by forest trees (Vogel et al., 1989).

Trees in conurbations are usually more exposed to metal deposition through human activities, such as intensive agriculture, industry, waste disposal and traffic, than forest trees. The responses of trees to soil pollution by metals have been investigated in particular to test their suitability for phytoremediation (Punshon et al., 1995; Punshon and Dickinson, 1997; Hammer et al., 2003; Keller et al., 2003; Rosselli et al., 2003; Vyslouzilova et al., 2003) or for biofuel production on

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contaminated land considered unsafe for food production (Landberg and Greger, 1996; Moffat et al., 2001). These investigations have mostly been made using plants grown in isolation in hydroponic systems or in pots. They have most often focussed on cadmium only (Godbold, 1991; Gussarson et al., 1995; Landberg and Greger, 1996; Österas et al., 2000; Österas and Greger, 2003). Österas et al. (2000) reported that increasing Cd in nutrient solutions reduced the shoot and root growth of *Betula pendula* seedlings, whereas *Pinus sylvestris* and *Picea abies* seedlings reacted only with reduced root growth. Zinc treatments of *Populus* × *euramericana* decreased foliage and total dry mass and also impaired gas exchange (Di Baccio et al., 2003). Inhibition of photosynthesis causes a decrease in growth, but a concurrent reduction in transpiration may also limit metal accumulation. Gas exchange measurements can therefore yield important information about reaction patterns in growth and metal accumulation. Tognetti et al. (2004) found that the reaction of the gas exchange to metal stress can vary considerably among species. Deciduous trees are reported usually to be more sensitive to metals than conifers (Patterson and Olson, 1983; Arduini et al., 1996). Certain fast-growing tree species, such as *Betula* spp. (Denny and Wilkins, 1987), *Salix* spp. (Kahle, 1993), and *Acer pseudoplatanus* (Turner and Dickinson, 1993), have, however, demonstrated a rather high tolerance to metals in soils. In particular, *Salix viminalis* has proved to be a very metal-tolerant tree species, accumulating up to 5.7 mg Cd kg^{-1} and 220 mg Zn kg^{-1} in the foliage (Greger and Landberg, 1995; Rosselli et al., 2003).

Much less is known about tree responses to mixed metal contaminations of soils under natural conditions and how these responses depend on other factors such as soil and climate conditions (Hagemeyer, 1999). Such knowledge would be particularly relevant if woody plants are to be used for stabilising and reclaiming polluted soil (Dickinson, 1996). Field studies are usually confronted with a large variability of soil and site conditions. Replicates and controls are therefore difficult to set up. It is virtually impossible to find two soils in which the only factor that differs is the degree of pollution. Consequently, it is extremely difficult to link effects with causes in field studies. For this reason, an intermediate approach between pot and field experiment was taken in an interdisciplinary project "From Cell to Tree" at WSL Birmensdorf (Switzerland). In this project, model ecosystems were set-up in lysimeters. Replicates of the same communities of young forest trees and understorey vegetation were grown on replicates of reconstituted soil in an environment close to field conditions. The main factor that was varied was the contamination of topsoil with metal-containing dust. This treatment simulated pollution by atmospheric deposition in the vicinity of a metal smelter. The acidity of the artificial rain used in irrigation and the type of subsoil (acidic vs. calcareous) were additional factors varied. This experimental set-up was motivated by a scenario in which metal-contaminated agricultural land is reclaimed by growing trees to stabilise the pollution and to use the land at the same time to produce wood, Christmas trees, or other forest products. Such uses of polluted land are expected to become increasingly important in the future. The following tree species, which are widely distributed and economically important in Europe, were selected for the experiment: Norway spruce (*Picea abies*) of economic value for timber production, silver birch (*Betula pendula*) as an early-succession species, European aspen (*Populus tremula*) as a cash crop for pulp wood and as a renewable energy source and common osier (*Salix viminalis*) for the phytostabilisation of slopes and biofuel production.

In the framework of the WSL project, we investigated the effects of the pollution on the metal accumulation, growth, and gas exchange of these tree species, and how these were influenced by rain acidity and the type of subsoil.

Our hypothesis was that increased metal accumulation will reduce the gas exchange and growth of trees on the metal-contaminated soil modified by the yearly changing climate. We expected that these effects would be more pronounced in combination with acidified irrigation because the solubility of metals in soil generally increases with decreasing soil pH. We further expected stronger effects on acidic than on calcareous subsoils because the latter have more favourable growth conditions, a better supply of base cations and other nutrients. Thus, the calcareous subsoil would allow the trees to grow more roots deeper into the soil to compensate for inhibited root development in the contaminated topsoil. Finally, we expected that *P. abies* would be less affected than the other species on acidic subsoils, because it is known as an acid-tolerant species, and that *S. viminalis* would be least affected on calcareous subsoils by the contamination of the topsoil due to its known metal-tolerance.

2. Materials and methods

2.1. Experimental design

The experiments were carried out in 16 hexagonal open-top chambers (OTCs), each 3 m in height, 3 m in width, and 21 m^3 in volume. Below ground each OTC consisted of two concrete-walled compartments (depth 1.5 m, ground area 3 m^2, volume 4.5 m^3). The bottoms of the compartments were filled in 1999 with a three-layered drainage packing of quartz sand and gravel of the following grain size: 5–8 mm at a depth of 150–120 cm, 1.5–2.2 mm at a depth of 120–110 cm, and 0.7–1.2 mm at a depth of 110–100 cm. On top of these quartz sand layers an 80-cm layer of subsoil was packed. In each OTC, the subsoil was calcareous (pH 7.4) in one compartment and acidic (pH 4.2) in the other. Finally, on top of each subsoil a 15-cm layer of topsoil (pH 6.4) was filled in. Relevant soil properties are given in Table 1. Because anthropogenous metal contaminations occur mostly in the topsoil and because we wanted to compare uncontaminated and metal-contaminated topsoil, an inherently agricultural topsoil with properties fitting to both subsoils (with slightly acidic pH) was selected after an extended evaluation process. This topsoil had the advantage that no nutrient deficiencies were introduced to the already multifactorial experimental design. Plant nutrient analyses were carried out for macro- and micronutrients in each year for each species. They varied between species and years. In both years, the metal-treatment significantly decreased phosphorus (P) from 3000 mg kg^{-1} to 2600 mg kg^{-1} in *P. tremula* leaves. In *S. viminalis*, small changes were detected in the first year, but not in the second year. In *P. abies*, P was decreased by the metal-treatment from 2600 mg kg^{-1} to 2300 mg kg^{-1}, however, P was not deficient.

The glass walls of the OTCs were kept partly opened for temperature regulation. The movable roofs closed automatically during rainfall in the vegetation period (May to October). The plants were irrigated by means of six