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Influence of soil aeration on rooting and growth of the Beuys-trees in Kassel, Germany

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ABSTRACT

Soil aeration is an important factor in tree growth. Oxygen must be taken from the atmosphere for root respiration, and carbon dioxide must be discharged to the atmosphere. Because the pore space of the soil could be considered the "dead end" of the free atmosphere, topsoil gas diffusivity is particularly important for soil aeration. Due to diverse land uses, several soil cover types alternate on a small scale at urban sites, competing with the natural function of soil as the living space for roots.

During Documenta 7 in 1982, the artist Joseph Beuys initiated the spectacular landscape art project "7000 Oaks". Seven thousand trees of approximately the same age were planted over the whole city of Kassel, Germany, offering best possible conditions for investigating the influence of specific site factors on root and tree development. At 8 different sites featuring 36 Beuys-oaks and 15 Beuys-planes, topsoil gas diffusivity, soil CO_2 concentration and soil respiration of different soil cover types were measured and correlated with fine root density and tree growth.

Topsoil gas diffusivity and soil respiration depend on soil cover type. The lowest gas diffusivities and respiration rates were found at sealed sites, and the highest values were measured at vegetated sites such as lawn or flower beds. Soil gas diffusivity primarily controls soil respiration. Soil CO_2 concentration is not strictly linked to the coverage type and does not show a strictly directed dependence on top soil gas diffusivity and soil respiration. Tree root density and height as well as diameter at breast height (1.3 m) of the oaks were decisively shaped by the gas diffusivity of the soil cover, whereas the investigated planes were not affected by soil aeration deficiencies. The vitality of urban trees can be controlled by the design of the tree site and the choice of the species.

Introduction

Beside the supply with water and nutrient, sufficient soil aeration is an important site factor for trees. Oxygen must be taken from the atmosphere for root respiration, and carbon dioxide must be discharged to the atmosphere. The continuous air-filled soil pores are the only connection between roots and the atmosphere. The volume and continuity of the air-filled pores thus control the quality of soil aeration (Flühler, 1973; Frede, 1986; Schack-Kirchner, 1994). If soil pore volume and soil pore continuity are reduced by compaction or sealing, roots cannot be supplied with oxygen and, conversely, CO_2 emissions from the soil are inhibited (Hildebrand, 1987; Herbauts et al., 1996; Horn et al., 2007).

Against the background of existing investigations, soil aeration deficiencies hamper root respiration (Qi et al., 1994; McDowell et al., 1999; Gaertig et al., 2002), leading to the functional loss of fine roots (Rickman et al., 1965; Gaertig et al., 1999). As a consequence of a reduced root system, the tree may fail to absorb sufficient water and nutrients, resulting in the deterioration of crown structure and declining growth (Aslanboga, 1976; Hetsch et al., 1990; Gaertig, 2001; Uhl, 2008; Gaertig et al., 2010). Detailed reviews concerning the influence of soil aeration deficiencies on plants are given by Stolzy and Letey (1964), Gliński and Stępniewski (1985) and Kozlowski (1999).

To investigate the functions of the soil for plant growth, structure parameters such as bulk density or pore volume are often used (Gilman et al., 1981; Hildebrand, 1983; Corns, 1988; Hetsch et al., 1990). However, information content of these parameters about soil aeration is limited (Hildebrand, 1983; Powers et al., 1998; Gaertig, 2007). This might be illustrated by the example of a foil lying on the ground: Gas exchange is interrupted, although soil structure has not been changed (Gaertig, 2007).

A convenient parameter to describe soil aeration is the relative gas diffusivity, also called relative apparent gas diffusion coefficient (Ball, 1987; Schack-Kirchner, 1994, 1996; Gaertig, 2007). It describes the diffusive flux between soil air and atmosphere, which is the primary mechanism for gas exchange (Gliński and

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Stępniewski, 1985). Furthermore, top soil CO_2 concentration can be used as integrative parameter to describe soil aeration (Schack-Kirchner, 1994; Gaertig et al., 2002; Pumpanen, 2003). Depending on soil respiration, i.e., respiration of roots and microorganisms, and soil gas diffusivity, the CO_2 concentration in the topsoil is up to 100 times higher than in the atmosphere (Gaertig et al., 2002; Pumpanen, 2003). Elevated CO_2 concentration in the soil atmosphere can be attributed to restricted gas exchange rather than to high soil respiration (Schack-Kirchner, 1994; Gaertig, 2001; Gaertig et al., 2002). As soil CO_2 can only be discharged to the atmosphere passing the soil–atmosphere interface, elevated CO_2 concentrations in the upper soil layers indicate soil aeration deficiencies throughout the whole rooting space.

Urban soils must fulfil numerous functions. On the one hand, they serve as foundations of transportation construction such as streets, parking places or pavements, which require soil to be covered with asphalt, flagstones or cobblestones. On the other hand, the same sites must be suitable as rooting space for urban trees.

Little information is available on how the different types of sealant affect soil gas diffusivity or how urban trees react to soil aeration deficiencies. This might be, because urban sites are tremendously heterogeneous, and it is difficult to find comparable clusters of trees growing at sites, which differ in soil aeration but not in further tree growth affecting variables, such as water and nutrient supply or pollutants.

During Documenta 7 in 1982, the artist Joseph Beuys initiated the spectacular landscape art project "7000 Oaks". Between 1982 and 1986, 7000 trees of different species were planted in Kassel, Germany, each paired with a columnar basalt marker. The planting of 7000 trees within a short time at different sites within the same city offered the best possible conditions to investigate the influence of specific site factors on root and tree growth.

This study examined the influence of different urban soil covers on soil aeration parameters, including topsoil gas diffusivity, soil CO_2 concentration and soil respiration, and the impact of soil aeration on fine root density, height and diameter at breast height of the trees.

Materials and methods

Investigation sites

The relationship between soil aeration, rooting and tree growth was investigated at the sites of 36 oaks (*Quercus robur* L.) and 15 planes (*Platanus* × *hispanica* Miller ex Münchh.) of the "7000 Oaks" project. The trees were distributed at 8 different urban sites in Kassel, Germany.

Sealants differ at each investigation site. The following sealants were investigated: macadamised road surface, sealed soil covers (including asphalt, flagstone and cobblestone), vegetated soils (including lawn, unkempt lawn and flower bed) and non-vegetated soils, which were often covered with gravel. The "flagstone" type of sealed soil cover includes concrete stones and concrete flagstones with gaps between 2 mm and 15 mm in size.

Sample design

Using a north-facing sample grid of the investigated trees, in each direction soil CO_2 concentration was measured once at 5 sample points, if buildings or roadways did not hamper measurements. Gas diffusion coefficients and soil respiration were measured once at 1–2 sampling points in each direction, depending on the heterogeneity of the soil covering (Fig. 1).

Root samples were taken at each sampling point of the combined gas diffusion/respiration measurement at 3 depths. Roots could not be excavated under sealed soil covers except for one site ("Tischbeinstr."), where it was possible to excavate root samples under flagstones. The numbers of observations at each investigation site and soil cover type are shown in Tables 1 and 2.

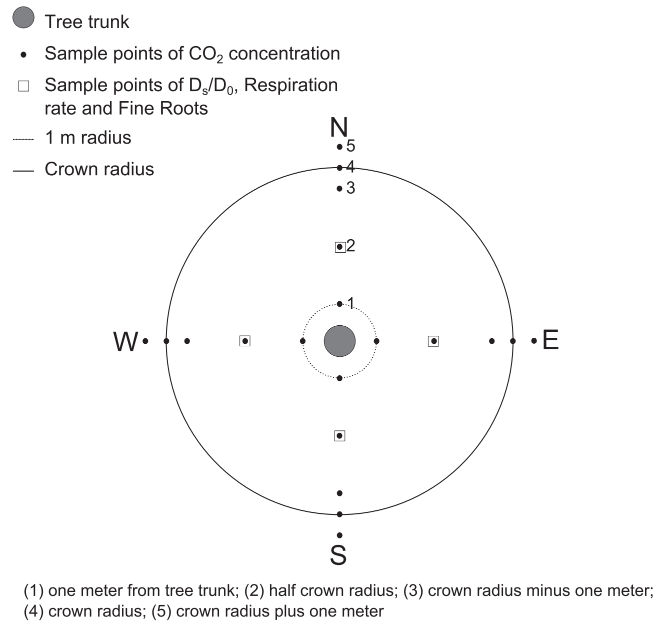

Fig. 1. Sample design of the measurement of topsoil CO_2 concentration, relative gas diffusivity, respiration rate and fine root density.

Soil cover

At all of the investigated tree sites, the percentage of each soil cover type was estimated within a circular area of 5 m radius. The areas were delimited with the software ArcGis10 (Esri Deutschland GmbH, Kranzberg, Germany) based on high resolution orthophotos from 2nd April 2009 and the topographic layer of the basic city map (municipality of Kassel – Vermessung und Geoinformation, 2010). Quality control was performed by means of ground truth.

Gas diffusion coefficient

Introduction

The common parameter describing the ability of soils to transport gases by diffusion is the relative diffusivity (Flühler, 1973; Gliński and Stępniewski, 1985; Frede, 1986). The diffusive flux of a gas in the atmosphere depends – at equal temperature and pressure – on the diffusion coefficient of the gas and the concentration gradient (Fick's Law). The transport of the gas in the soil towards the transport in the atmosphere is always reduced by the resistance of the substrate. The resistance depends on the air-filled pore volume (ε) and the relative diffusion efficiency (γ). The diffusive transport of gas in the soil can therefore be described by

$$D_s = D_0 \gamma \varepsilon \quad (1)$$

where D_s is the apparent gas diffusion coefficient of the soil [$cm^2\,s^{-1}$] and D_0 the diffusion coefficient of the gas in the atmosphere [$cm^2\,s^{-1}$]. By transformation of the equation, we obtain the dimensionless relative diffusivity D_s/D_0. The D_s/D_0 describes how molecular diffusion through the soil is reduced, compared to the diffusion in the atmosphere. A D_s/D_0 of 0.1 means that the gas flux through the soil amounts to 10% of the flow within the atmosphere (Gaertig, 2001).