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Water table fluctuations and soil biogeochemistry: An experimental approach using an automated soil column system

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SUMMARY

Water table fluctuations significantly affect the biological and geochemical functioning of soils. Here, we introduce an automated soil column system in which the water table regime is imposed using a computer-controlled, multi-channel pump connected to a hydrostatic equilibrium reservoir and a water storage reservoir. The potential of this new system is illustrated by comparing results from two columns filled with 45 cm of the same homogenized riparian soil. In one soil column the water table remained constant at −20 cm below the soil surface, while in the other the water table oscillated between the soil surface and the bottom of the column, at a rate of 4.8 cm d^{-1}. The experiment ran for 75 days at room temperature (25 ± 2 °C). Micro-sensors installed at −10 and −30 cm below the soil surface in the stable water table column recorded constant redox potentials on the order of 600 and −200 mV, respectively. In the fluctuating water table column, redox potentials at the same depths oscillated between oxidizing (~700 mV) and reducing (~−100 mV) conditions. Pore waters collected periodically and solid-phase analyses on core material obtained at the end of the experiment highlighted striking geochemical differences between the two columns, especially in the time series and depth distributions of Fe, Mn, K, P and S. Soil CO_2 emissions derived from headspace gas analysis exhibited periodic variations in the fluctuating water table column, with peak values during water table drawdown. Transient redox conditions caused by the water table fluctuations enhanced microbial oxidation of soil organic matter, resulting in a pronounced depletion of particulate organic carbon in the midsection of the fluctuating water table column. Denaturing Gradient Gel Electrophoresis (DGGE) revealed the onset of differentiation of the bacterial communities in the upper (oxidizing) and lower (reducing) soil sections, although no systematic differences in microbial community structure between the stable and fluctuating water table columns were detected.

1. Introduction

The transition zone separating the soil from the underlying groundwater plays a major role in regulating the flows of carbon, nutrients and contaminants at the watershed scale (Hancock et al., 2005; Hefting et al., 2004; Sophocleous, 2002; Triska et al., 1989). The capillary fringe and the adjacent unsaturated and saturated zones are characterized by steep physical–chemical gradients, which tend to focus biogeochemical activity. Of particular importance are the concentration gradients of electron donors and acceptors, as they are intimately linked to the pathways, rates and products of many biogeochemical processes (Borch et al., 2010). In addition to spatial gradients, fluctuations in the water table may cause large temporal variations in local redox conditions (Vorenhout et al., 2004; Haberer et al., 2012), soil water content and matric potential. The limited existing data indicate that oscillating redox conditions modify the biogeochemical and microbial dynamics of subsurface environments (Blodau and Moore, 2003; Pett-Ridge et al., 2006; Weber et al., 2009), while changes in soil matric potential may further affect the mobility of organic substrates and the diffusion of nutrients and gases (Drenovsky et al., 2004; Griffiths et al., 2005; Schimel et al., 2007).

Variations in the position of the water table and the associated variations in redox conditions may impart unique geochemical and mineralogical signatures to the soil interval over which the water table fluctuates. One example is the presence in this interval of mixed valence iron minerals of the green rust group (Trolard et al., 2007). Microbial communities in the same depth interval may adapt to the continuous changes in water saturation and redox potential by developing a greater functional diversity and flexibility, compared to subsurface communities living under more

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stable conditions (Pett-Ridge and Firestone, 2005). Redox oscillations have been proposed to result in a more complete degradation of organic matter in bioturbated marine sediments (Aller, 1994), but a similar effect of redox oscillations on soil organic matter degradation remains to be unequivocally demonstrated (Pulleman and Tietema, 1999). As soil microbial activity is intimately linked to the dynamics of biogenic gases (CO_2, CH_4, N_2O, methylated products), water table fluctuations are also expected to modulate gas exchanges with the atmosphere (Bubier et al., 1995; Moore and Knowles, 1989; Yavitt et al., 1997; Haberer et al., 2012).

One approach to unravel the biogeochemical implications of water table fluctuations is to conduct experiments with soil columns in which the position of the water table can be manipulated. Previous column studies have typically relied on a manual adjustment of the water table (Dobson et al., 2007; Legout et al., 2009; Farnsworth et al., 2012; Sinke et al., 1998; Williams and Oostrom, 2000). Here, we introduce a novel soil column system where the time course of the water level is imposed via a programmable multichannel pump. The system allows one to run two soil columns in parallel, with independent, pre-determined adjustment of the water levels. The use of the system is illustrated by presenting the results of an experiment with two columns that initially contained the same homogenized riparian soil. In one column the water table was maintained at a constant, mid-column level, while in the other the water level continuously oscillated. For the latter, the amplitude and periodicity of the water table fluctuations were representative of those observed in the watershed where the soil was collected. The average water depth in the fluctuating water table column coincided with the constant water level in the stable water table column.

The goal of the experiment was to better delineate the role of water table oscillations in the biogeochemical functioning of soils, by comparing soil respiration and geochemical properties under the stable and fluctuating water table regimes. Our hypothesis was that the most pronounced differences in organic carbon mineralization rates, microbial community structure and soil geochemistry would be found in the midsection of the columns, that is, within the depth interval where redox conditions and water content would deviate most significantly between the two soil columns. In addition to monitoring CO_2 emissions from the columns, pore waters were sampled periodically to follow the time-dependent distributions of diagnostic aqueous constituents. Vertical solid-phase concentrations of selected cations (Ca, K, Na), redox-active metals (Fe, Mn), organic carbon and nutrient elements (P, N, Si, S) were measured at the end of the 75-day experiment, in order to evaluate the effects of water table oscillations on soil biogeochemical transformations, elemental redistributions and the resulting geochemical depth profiles. To assess whether distinctive phylogenetic signatures emerged under the two different water table regimes, we extracted and compared DNA from the soil columns at the beginning and end of the experiment.

2. Materials and methods

2.1. Soil column system

A schematic diagram of the column set-up is shown in Fig. 1 (A picture of the experimental setup is provided as Supplementary Fig. 1). The columns, including the soil column and two auxiliary (equilibrium and storage) columns, are made of hard acrylic (wall thickness: 0.6 cm, inner diameter: 7.5 cm, length: 60 cm, Soil Measurement Systems, LLC, USA, model CL-021). The auxiliary columns control the water table level. The soil column has regularly spaced ports for sensors and pore water sampling. A filter membrane (Soil Measurement Systems, LLC, USA, bubbling pressure: 600 mbar) closes off the bottom of the column and a nylon mesh (Soil Measurement Systems, LLC, USA, bubbling pressure: 32 mbar) the top. For each column, three steel rods connect the acrylic top and bottom lids and are secured with bolts. Each lid has two ports. The entire system consists of two identical sets of three columns, which can be run in parallel.

As the labels imply, the equilibrium column is used to set the position of the water level in the soil column, while the storage column supplies water during water table rise and stores it during drawdown. A computer-controlled, multi-channel pump (9-channel Tower II pump, CAT. M. Zipperer, GmbH, Germany) regulates the flow of water between the columns. Each channel of the pump can be operated independently, with flow rates ranging from 5 μl min^{-1} to 10 ml min^{-1}. The three columns are connected to one another with chemically resistant blue polyurethane tubing (*Ark-Plas Products Inc*, *USA*, Cole-Parmer #95867-22) as illustrated in Fig. 1. When pump channel A or B is activated, the water level in the soil and equilibrium columns is lowered or raised, respectively.

The column system can be operated in a variety of configurations and water level regimes. In the configuration used here, the soil surface was kept exposed to air by having one of the ports of the upper lid open at all times (Fig. 1). To minimize evaporative water loss, the port has only a small opening (3 mm diameter). Except for this port, the system was kept completely airtight. The headspaces of the soil column and the two auxiliary columns were connected. That is, no attempt was made to exclude oxygen from the water in the auxiliary columns. For other applications, it is possible to use the upper ports of the columns to flush the headspaces with a given gas or gas mixture, for example when strict anoxic conditions need to be maintained.

2.2. Soil

The two soil columns contained soil from the riparian zone of Laurel Creek near the campus of the University of Waterloo (43°28′13″N, 80°33′20″W). The upper 15 cm of soil was collected along the unvegetated bank of the creek on October 20, 2011. By selecting an unvegetated soil, effects related to plant activity, including root respiration and exudation, were eliminated from the experiment. Surface water from the creek was obtained at the same location. The sediment was manually homogenized before introducing it into the columns. Both soil columns were packed with 45 cm of soil, leaving a headspace of 650 cm^3. In what follows, all depths are referenced with respect to the soil surface.

Basic physical and hydraulic properties of the homogenized and repacked soil, including porosity, bulk density and hydraulic conductivity, were measured using standard procedures (Klute and Dirksen, 1986). The bulk density (ρ_b) was determined gravimetrically after oven-drying the soil at 105 °C for 24 h (Gardner, 1986). The saturated hydraulic conductivity (K_{sat}) was determined using the constant head method. Soil moisture content was determined gravimetrically after drying approximately 20 g of fresh soil at 105 °C for at least 48 h. Values of K_{sat}, porosity and ρ_b were 310 cm day^{-1}, 0.43 and 1.04 g cm^{-3}, respectively.

Powder X-ray diffraction (XRD) on freeze-dried samples of the homogenized soil revealed the presence of quartz, feldspars, Ca and Mg carbonates (dolomite, aragonite and calcite), as well as Fe and Mn minerals (Supplementary Fig. 2). Diffraction peaks were matched to possible mineral phases using the tables in Chen (1977). Common Fe soil oxide minerals such as goethite and hematite could not be detected, but magnetite (d(Å) = 2.96, 1.60 and 1.53) and ankerite (d(Å) = 1.81), a Fe and Mn containing carbonate mineral closely related to dolomite, were both identified. Diffraction peaks diagnostic of pyrolusite (d(Å) = 3.15 Å), and periclase