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Lysimeter monitoring as assessment of the potential for revegetation to manage former iron industry settling ponds

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HIGHLIGHTS

- The Technosol provides a regulating service by retaining water and metals.
- High retention capacity is due to soil composition and physico-chemical properties.
- Dense and deeply-rooted vegetation cover limits water and solute fluxes.
- Settling ponds of iron industry could be managed by monitored revegetation.

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ABSTRACT

To assess the impact of metal-rich brownfields on groundwater quality, the fluxes in a Technosol developed on a former iron industry settling pond were studied. Intact soil monoliths (1 $m^2 \times 2$ m) were extracted and placed in lysimeters. Dynamics of fluxes of metals and solutes under varying vegetation cover were monitored over the course of four years. Soil hydraulic properties were also determined. Results showed that the Technosol has a high retention capacity for water and metals, in relation to its mineral components and resulting chemical and physical properties. As a consequence, metal fluxes were limited. However, soluble compounds, such as SO_4^{2-}, were found at significant concentrations in the leachates. The presence of a dense and deeply-rooted vegetation cover limited water- and solute-fluxes by increasing evapotranspiration and water uptake, thereby reducing the risks of transfer of potentially toxic compounds to local groundwater sources. However, vegetation development may induce changes in soil chemical (e.g. pH, redox potential) and physical properties (e.g. structure), favoring metal mobilization and transport. Revegetation is a valuable management solution for former iron industry settling ponds, provided vegetation does not change soil physico-chemical conditions in the long term. Monitored natural attenuation is required.

1. Introduction

As legacies of industrial history, brownfields require appropriate management to minimize their environmental impact. Sites can be spontaneously colonized by vegetation and other living organisms, which gives rise to specific ecosystems. As such, a series of ecosystem services may be expected, among which regulation of water quality and quantity is a primary goal (Morel et al., in press).

In brownfields, artifacts derived from past industrial activities evolved under the influence of environmental factors, i.e. climate and organisms, and generated a large variety of Technosols (IUSS Working Group WRB, 2014). The ability of Technosols to regulate water quality and quantity has yet to be adequately addressed. Brownfields may contain substantial amounts of pollutants (e.g. heavy metals), the fate of which is of primary importance and strictly dependent on the functioning and evolution of the Technosols.

In Europe, the decline of the steel and iron industry has led to the closure of numerous sites at the end of the 20th century. This industry has generated various by-products, including sludge resulting from

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scrubber wet cleaning of blast furnace fumes. Blast furnace sludge (BFS) was not recycled because of its high Zn, Pb and alkali metal content, and was often dumped into settling ponds. For example, in the Lorraine region (North-East of France), the quantity of sludge stored in industrial settling ponds was estimated at 2.10^6 tons in 14 sites (ArcelorMittal Real Estate France, internal assessment). A major drawback of storage in settling ponds is the risk of groundwater contamination by metal-enriched leachates. Moreover, regulations no longer tolerate long-term storage of waste on industrial areas (Van Herck et al., 2000).

After dumping termination, ponds may be spontaneously colonized by vegetation or deliberately vegetated despite the a priori unfavorable nature of the substrate for plant growth. As a result, forest ecosystems may become established in relation to low bioavailability of the potentially toxic compounds, e.g. heavy metals or cyanides (Huot et al., 2013; Mansfeldt and Dohrmann, 2001, 2004).

Revegetation is a viable management solution for tailing ponds (Mendez and Maier, 2008), or industrial and urban brownfields, because it is more ecologically beneficial and less expensive than the standard dig and dump approach (Hartley et al., 2012; Vangronsveld and van der Lelie, 2003). Indeed, plant canopy reduces eolian dispersion while plant roots significantly decrease erosion by water and leaching (Mendez and Maier, 2008), thereby limiting risks of pollutant transfer to other ecosystem compartments. However, the long-term colonization of brownfields (e.g. slag heap) by plants and the incorporation of organic matter may affect the leachability of metals (Houben et al., 2013). In particular, roots can modify the soil structure and water flow patterns by creating biopores, and so, preferential pathways for drainage (Bodner et al., 2013). Activity of roots and associated microorganisms may increase element availability by modifying chemical ambience (e.g. pH; Marschner and Römheld, 1983) and by releasing organic ligands (Hinsinger et al., 2009; Morel et al., 1986).

Vegetated former settling ponds provide useful information regarding the sustainability of management solutions based on vegetation. Here, we have studied the dynamics of fluxes of metals and solutes in a Technosol using lysimeter experiments. The studied Technosol developed on a former iron industry settling pond and is presently covered by forest. The lysimeter device is suitable for long-term monitoring of contaminants in the soil–plant–water system (Roulier et al., 2008). It gives information regarding potential transfer of contaminants towards organisms and groundwater by providing concentrations in soil solutions, which can be absorbed by organisms, and in leachates, which contribute to groundwater recharge. With the aim of predicting soil evolution, it allows for acquisition of useful data to characterize hydrodynamic behavior and to simulate water flow (Séré et al., 2012; Ngo et al., 2013a,b) and solute transport (Ngo et al., 2015) at an intermediate scale between laboratory and field scales.

Previous investigations carried out on this soil revealed high concentrations of metals, especially Pb and Zn (Huot et al., 2013). Mineralogy is dominated by poorly crystalline compounds and composed mainly of Mn and Fe (hydr)oxides, aluminosilicates and carbonates (Huot et al., 2014a). Organic matter is mainly of anthropogenic origin except for the input of vegetation debris in the surface layer (Huot et al., 2014b). These materials are characterized, at the chemical level, by an alkaline pH and a high CEC, and at the physical level by a high porosity associated with a high water retention capacity. As a result, this soil was classified as a Spolic Technosol (Andic, Calcaric, Hydric, Laxic, Thixotropic, Toxic) according to the WRB (Huot et al., 2013). These properties may suggest a low availability and mobility of metals in the soil.

In this study, fluxes of metals and soluble compounds were monitored over four years through soil monoliths extracted in the settling pond under the influence of real climatic conditions and varying vegetation cover (from bare soil to dense deeply-rooted planted forage including spontaneous herbaceous cover). Lysimeter experiments were coupled with the determination of hydraulic properties by the evaporation method to:

i) assess the regulating role of the high metal content Technosol with regards to water quality and quantity by monitoring the dynamics of water and solute fluxes in relation to its chemical and physical properties, and
ii) assess the influence of vegetation cover (type, density) on water and solute fluxes at the lysimeter scale and discuss the long-term potential for revegetation as an approach to sustainable management for similarly contaminated sites.

2. Materials and methods

2.1. Site

The site is a former settling pond of the steel and iron industry complex of Pompey–Frouard–Custines (Lorraine, France), operating from 1872 to 1986. It is located on an island at the confluence of the Moselle and the Meurthe rivers. The geological substratum is composed of marly formations of Lias covered by a 7-m thick layer of alluvia from both rivers. Alluvial materials were partially or totally extracted and by-products from the iron industry, mainly blast furnace sludge, were dumped into the pond likely until the beginning of 1950s, thereby generating stratified deposits (26 000 m^2 area and ca. 10-m deep). Following the termination of dumping, vegetation has developed spontaneously, and the pond has been covered by a diversified deciduous forest (Fig. 1a and b). The alluvial groundwater table is 7–9 m from the pond surface.

2.2. Sampling of soil monoliths

Two soil monoliths (2-m deep and 1 m^2 surface area) were sampled by core-drilling in the northwestern part of the settling pond, at a distance of 2 m from each other. Sampling began in June 2009 by the French Scientific Interest Group — Industrial Wasteland (GISFI) in collaboration with Umwelt-Geräte-Technik (Müncheberg, Germany) (Fig. 1b and c). The method preserves the soil structure and vegetation cover to the greatest extent possible. Three successive 5-cm gravel and sand layers were placed at the bottom of the lysimeters. Then, both lysimeters (A and B) were installed at the GISFI experimental station (Homécourt, Meurthe-et-Moselle, France) in a designated buried cell (Fig. 1d).

Monolith excavation generated two pits displaying the superimposition of contrasted sub-horizontal layers corresponding to the settling of successive sludge supplies and an organo-mineral horizon at the surface. The profile corresponding to the extraction of lysimeter B was described in further detail in Huot et al., 2014a while the profile corresponding to the extraction of lysimeter A was globally similar, with the major exception of a pocket of coarser materials between 60 and 120 cm-depth.

2.3. Lysimeters

Lysimeters were placed on a weigh system with 100 g precision. At the bottom, leachate flow was measured using a tipping counter and leachates were collected in glass bottles. Lysimeters were equipped at three depths (50, 100 and 150 cm) with time domain reflectometry (TDR) probes (TRIME-IT, IMKO) to measure volumetric water content, equitensiometers (Tensio 300, UGT) at 50 cm and tensiometers (Tensio 151, UGT) at 100 and 150 cm to measure water potential, temperature sensors and suction cups to collect soil solution (Fig. 2).

Climatic conditions (precipitation, wind speed and direction, air pressure, temperature and humidity, sunshine rate) were recorded