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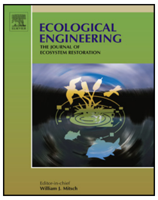

# Predicting the toxicity of post-mining substrates, a case study based on laboratory tests, substrate chemistry, geographic information systems and remote sensing

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## ABSTRACT

Approaches were evaluated for predicting the spatial distribution of phytotoxicity of post-mining substrates. Predictions were compared with empirical data measured in the field (a heap at a post-mining site) and laboratory. The study was performed in a highly variable 1-ha plot that was overlain with a regular grid of sampling points (with 5 m between adjacent grid points). At each of 21 points, soil pH, conductivity, and arsenic content were measured, and soil was sampled and used in a laboratory germination test with *Sinapsis alba*. At each grid point, a field germination test with *S. alba* was also conducted, and spontaneous vegetation was removed and weighed. At the same time, air-borne hyperspectral imagery data of the site were acquired, and field spectral characteristics of dominant substrates were measured. This enabled automatic substrate classification, which was used to map the spatial distribution of the substrates.

*S. alba* germination in the laboratory was closely correlated with *S. alba* germination in the field ($r = 0.918$), and both were correlated with the biomass of spontaneously established vegetation in the field. Substrate pH and substrate type were the best predictors of *S. alba* germination at points between the grid points. *S. alba* germination was well predicted ($P = 0.001$) by (1) direct interpolation of toxicity between grid points ($R^2 = 0.51$) and by (2) substrate classification based on hyperspectral images ($R^2 = 0.56$).

## 1. Introduction

Open cast mining cause large disturbance of ecosystem. In this kind of mining, a large amount of overburden material overlaying layers of mined deposit is excavated and deposited in vast spoil heaps. Consequently the affected ecosystems are destroyed (excavated or buried) by this practice. Recovery of post-mining ecosystems and especially of their soils and plant communities is a basic precondition for socioeconomic development in areas affected by mining (Bradshaw, 1997). Post-mining substrates differ markedly from ordinary soils. Most importantly, post-mining substrates lack structure, have extreme textures (a large proportion of particles that are either too coarse or too fine), and are in some cases toxic to plants (Bradshaw, 1997). Phytotoxicity following coal mining may occur for several reasons. The most common would be weathering of pyrite or similar sulfur-rich minerals, which results in low soil pH, high electrical conductivity (high salt content), and increased content and mobility in some metals and other toxic elements (Jenner and Janssenmommen, 1993; Bradshaw, 1997; Sample and Suter, 2002; Frouz et al., 2005; Gomes et al., 2014).

Phytotoxicity of post-mining soil can substantially slow soil development and the recovery of vegetation and of the entire ecosystem. Timely prediction of overburden substrate toxicity is

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therefore essential for understanding and managing reclamation. Although substrate toxicity can be predicted based on substrate pH, the toxicity can also result from high salinity, high metal content, or a combination of these and other factors (Frouz et al., 2005). It follow that biological tests that reflect the complex influences of several environmental factors may be more useful than assessment of pH alone for predicting substrate phytotoxicity (Frouz et al., 2005). These biological tests are very efficient in ranking various post-mining substrates according to toxicity (Frouz et al., 2011). Biological tests have also shown that substrates that were toxic to plants were also toxic to soil algae and invertebrates (Römbke et al., 2006; Frouz et al., 2011). However, toxicity is only one of many factors that affect a species in the field, and only a limited number of organisms are used in toxicity tests; as shown in study using plans, soil algae and soil invertebrates, generalizing the results obtained with these model organisms to the whole community must be done with caution (Frouz et al., 2011).

Another useful approach for predicting substrate phytotoxicity is to relate toxicity to the mineral composition of the overburden because individual minerals show good correlation with substrate toxicity (Frouz et al., 2005; Rojík, 2014). The advantage of using individual types of rock or sediments with specific minerals composition is that particular types of rock typically have some characteristic combination of individual chemical properties. As a consequence determination of rock or sediment type may in fact bring more complex information that analysis of just one chemical parameter.

In addition to the level of toxicity in a particular area, the spatial distribution of toxicity is important for reclamation practice. One possibility is to determine either toxicity or some chemical substrate properties related to toxicity in points with known coordinates and then interpolate values between points by geostatistic analysis and kriging using geographic information systems (GIS) (Alam et al., 2015). Another option would be to map various substrates on the heap and account toxicity as property of given substrate. However manual mapping may be logistically difficult to arrange in large areas. Spectroscopy is useful for distinguishing minerals (Kruse et al., 2003) and rocks (Zhang and Li, 2014), and hyperspectral imagery and field spectroscopy can be used to determine their spatial distribution (Zhang and Li, 2014). As noted, the substrate type can be used to predict its phytotoxicity. It follows that hyperspectral imagery and field spectroscopy might be used to predict spatial distribution of phytotoxicity.

The aim of the current study is to compare three approaches for predicting spatial distribution of phytotoxicity on post-mining sites. In one approach, we measured phytotoxicity at grid points on the heap and then used interpolation to predict phytotoxicity at other points on the heap using GIS techniques. In a second approach, we measured substrate pH at grid points on the heap and then used interpolation and the relationship between substrate pH and phytotoxicity to predict phytotoxicity at other points on the heap. In a third approach, we used airborne hyperspectral imagery and field spectroscopy to map the distribution of various types of post-mining substrates, and then used the relationship between substrate type and phytotoxicity to predict phytotoxicity at other points on the heap. The predictions were compared with empirical measurements of phytotoxicity in another set of points which was not use to generate predictive models.

## 2. Materials and methods

### 2.1. Study sites

The study was conducted in West Bohemia near Sokolov on a heap Podkrušnohorská výsypka (Frouz et al., 2001, 2008), which is an artificial hill, created by overburden from brown coal-mining, that rises about 150 m above the surrounding terrain (elevation of 590 m a.s.l.) and is about 8 km long and 4 km wide. The mean annual precipitation is 650 mm, and the mean annual temperature is 6.5 °C (Frouz et al., 2001). The highest temperature is in July (15 °C) and the lowest in January (−4 °C). The material of the heap is dominated by alkaline tertiary clays and tuffites. A plot in central part of heap with an area of about 1 ha (50°13′55.790″N, 12°39′4.428″E) was used in this study. The plot was selected for this study because it was used in previous research (Frouz et al., 2005, 2011) and because, based on previous knowledge, it contain large variability of post mining substrates. The plot has a mixture of substrate types including, jarosites, cypris clays, tuffites, and coal-rich kaoline clays. This part of the heap was dumped in 1995 and has not been subjected to any reclamation effort. In 2011, about 80% of the plot was bare ground, plants covered up to 20% of the area; *Phragnites australis* was dominant in the moist parts, and *Calamagrostis epigeios* was dominant in the dry parts. In middle of the plots was flooded depression about 20 × 10 m, which was not used in this study.

### 2.2. Soil sampling

In April 2011, a 4 × 6 grid of points with 5 m between adjacent points was established in the middle of the study site. Of the 24 points, only 21 were sampled because three fall into a pond and thus were not sampled. At each of the 21 sampling points, the type of geological substrate was determined based on the description of Rojík (2014); as indicated in the Results, the four types of substrate were cypris clay, tuffites, jarosite, and coal-rich clay. A composite soil sample consisting of three subsamples at 0–5 cm depth was collected at each point. Individual subsamples were taken in circle 20 cm in diameter with grid point in the middle and were located north, southwest and south east from sampling point. A field phytotoxicity test was conducted at each point as described in the next section. To determine the distribution of the naturally occurring vegetation, vegetation in a 0.25-$m^2$ area at each point was cut at ground level, dried (at 60 °C for 48 h), and weighed.

A grid point samples were used to create predictive spatial model of toxicity and substrate chemistry described below. To test these model predictions, 18 control points were randomly located within the area covered by the grid. At each control point, the type of geological substrate was determined, and a composite soil sample was taken from 0 to 5 cm depth the same way as described above.

To explore effect of the four types of substrates on soil pH and on phytotoxicity in the laboratory, we used substrates sampled from the grid points. For each type of substrate, the first six samples collected were used. If fewer then six samples were available for a substrate type, additional samples of that substrate were taken in the grid area but not immediately adjacent to points where substrate was previously sampled. After the pH of these samples was determined, their phytotoxicity was assessed in the laboratory as described in the next section.

### 2.3. Phytotoxicity tests

Phytotoxicity was assessed based on seedling establishment of *Sinapis alba* produced in laboratory test. For the laboratory phytotoxicity test, the soil samples from all grid and control points was air-dried at room temperature, crushed, spread in a layer about 3 cm thick in a round pot (12 cm diameter), and sown with *S. alba* seeds (20/pot). Each sample was represented by three replicate pots. The pots were kept in the laboratory under natural light and temperature conditions and were watered regularly. The pots were separated so that drainage water was not exchanged between pots.