Geoderma 308 (2017) 69–77

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Magnetometric assessment of soil contamination in problematic area using empirical Bayesian and indicator kriging: A case study in Upper Silesia, Poland

Piotr Fabijańczyk[a,*], Jarosław Zawadzki[a], Tadeusz Magiera[b]

[a] Warsaw University of Technology, Faculty of Building Services, Hydro and Environmental Engineering, Nowowiejska 20, 00-661 Warszawa, Poland
[b] Institute of Environmental Engineering, Polish Academy of Sciences, M. Skłodowskiej-Curie 34, 41-819 Zabrze, Poland

ARTICLE INFO

Handling Editor: Yvan Capowiez

Keywords:
Soil pollution
Soil magnetometry
Geostatistics
Problematic areas
Empirical Bayesian kriging
Indicator kriging

ABSTRACT

Although soil magnetometry is already frequently used to determine the extent of anthropogenic soil pollution, intensive effort is still needed to improve the effectiveness of magnetometric surveys. The main goal of our study was to estimate the spatial distributions of the probability that surface soil magnetic susceptibility exceeds critical levels in a problematic area. To do so, three advanced geostatistical methods, namely indicator kriging, empirical Bayesian kriging, and indicator cokriging (IC), were employed and the results were compared. The study area was located in a complex urban-industrial region located in Upper Silesia, Poland. The critical levels of soil magnetic susceptibility were equal to 30×10^{-5}, 50×10^{-5}, 75×10^{-5}, and 100×10^{-5} SI. The validation of results was done using both measurements of magnetic susceptibility in soil profiles and measurements of concentrations of As, Cd, Fe, and Zn in soil.

It was found that EBK, which offered the possibility of simulation of variogram parameters, was a particularly useful method of analyzing magnetometric measurements, especially when sparse and spatially irregular field measurements were carried out.

It was found also that in heavily polluted areas where extreme values of soil magnetic susceptibility are measured, a use of log-transformed data in EBK, may result in slightly overestimated predictions.

1. Introduction

Soil magnetometry is an emerging technique that is still being developed as a method of detecting and determining potential soil pollution with heavy metals or Potentially Toxic Elements (PTEs) of anthropogenic origin, which are emitted mainly by industry and transportation. Numerous studies have confirmed the high efficiency of soil magnetometry as a field technique in assessing the degree of pollution and the spatial extent of the polluted area (Petrovský et al., 2000; Spiteri et al., 2005; Fürst et al., 2009; Cao et al., 2015a; Łukasik et al., 2015). Although the development of soil magnetometry is at an advanced stage, the majority of studies have focused on the development of integrated field and laboratory measurement techniques for soil pollution studies. There are relatively few studies focusing on problems related to the processing of the magnetometric data. Some of them focus on the use of selected geostatistical techniques, such as variograms or various types of kriging (Zawadzki and Fabijańczyk, 2007; Cao et al., 2015b; Fabiańczyk et al., 2016). There are also studies on the use of regression-based methods (Fürst et al., 2010a, 2010b) or the multivariate approach (Guagliardi et al., 2013) to develop a comprehensive model of spatial variability of magnetic susceptibility (κ). In this study, κ values were integrated with additional environmental parameters related to geology, topography, and stand type. Other possible spatial techniques are regression kriging, which combines multiple linear regression and ordinary cokriging (Myers, 1984; Zhang et al., 1992), and geographically weighted regression (Hengl et al., 2004; Hengl, 2007; Ribeiro et al., 2016), which is a local form of linear regression used to model spatially varying relationships (McBratney et al., 2000; Scull et al., 2003; ESRI, 2014). However, these techniques have some weaknesses that make them not very useful in field magnetometry. For instance, they require assumptions that are difficult to fulfill, such as data normality, lack of multicollinearity, homoscedasticity, and most importantly, linearity between the outcome variable and the independent variables. However, the relationship between soil and auxiliary variables is often nonlinear and noisy (Hengl et al., 2004). Besides, regression kriging and geographically weighted regression may not be useful methods for field magnetometry due to the small data sets.

* Corresponding author.
E-mail address: piotr.fabijanczyk@pw.edu.pl (P. Fabijańczyk).

http://dx.doi.org/10.1016/j.geoderma.2017.08.029
Received 6 April 2017; Received in revised form 31 July 2017; Accepted 18 August 2017
Available online 30 August 2017

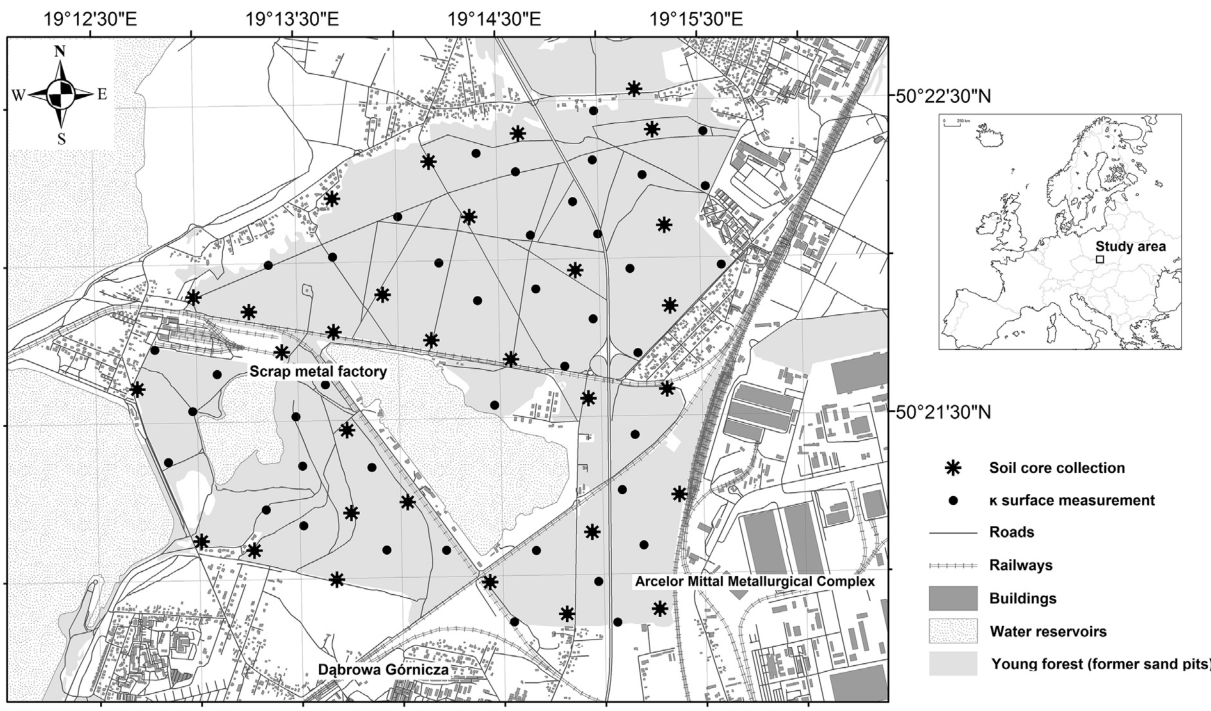

Fig. 1. Location of the study area, and spatial distribution of sample points.

It is important to gain knowledge about how to select the most appropriate methods of analyzing the spatial variability of κ, investigating correlations between κ and the concentration of PTEs, calculating spatial distributions, and finally determining the extent of potentially polluted areas. There is another important reason for the development of analytical methods of data interpretation in soil magnetometry. As it was initially intended, soil magnetometry is usually used in problematic areas, where numerous environmental factors such as soil type, land cover, or forest stands are spatially very variable. Consequently, it is necessary to use sufficiently robust calculation methods to analyze measured values of κ.

One of the possible directions of development of analytical methods in soil magnetometry is the use of a series of maps of the probability that κ exceeds some critical level (z_k). This probability will be denoted hereafter as $P_{\kappa > zk}$. Such maps may be useful for assessing potential soil contamination, as their interpretation can be based on the probability of contamination. $P_{\kappa > zk}$ can be easier to use than absolute values of magnetic susceptibility, which are often difficult to interpret.

As it was previously studied (Strzyszcz and Magiera, 2003; Łukasik et al., 2016), the determination of universal z_k values can be difficult, because these values depend on the natural magnetic background of the study area. Some suggested threshold values have been reported in the literature, although they should be considered only as baseline values to further define the z_k values for the area under investigation. The z_k thresholds can be values of κ related to potential soil pollution that have been estimated using pilot chemical measurements or based on previous experience. In this way, it is possible to calculate probability maps that can be used to investigate which parts of the study area are the most likely to be polluted (Papritz and Füchler, 1994; Wackernagel, 1994; Webster and Oliver, 2000; Rivoirard, 2004).

A more flexible approach to the determination of z_k values of κ can be the use of indicator methods that make it possible to delineate areas with high $P_{\kappa > zk}$ values. It is possible to use indicator kriging (IK), which does not require the data to be normally distributed. This is an important feature, because statistical distributions of environmental data are very often characterized by significant skewness as a result of the occurrence of extreme values. IK, however, also has some limitations. The stationarity assumption needed for IK is stronger than that required for ordinary kriging. Accordingly, it is necessary to define the homogeneous areas within the study site in order to carry out the IK procedure (Journel, 1983). Defining the homogenous soil zones in problematic, complex urban and industrial areas may be difficult. Numerous technosols developed on anthropogenic backgrounds with different chemical and mineralogical compositions and poorly developed or even undeveloped soil horizons may be present in such areas (Uzarowicz and Skiba, 2011; Uzarowicz and Zagórski, 2015). Even in the case of natural soils, the physical transformation of soil horizons usually results in high variability of the measured parameters (Łukasik et al., 2015). As a consequence, determination of the parameters of spatial correlations of κ may be difficult.

As can be found in the literature, empirical Bayesian kriging (EBK) offers many advantages over other types of kriging (Pilz and Spöck, 2007; Adhikary et al., 2011; Krivoruchko and Gribov, 2014). In EBK, variograms of κ are simulated several dozen times, and after that, parameters of variograms models were calculated on the basis of simulated values. Such an approach makes it possible to increase the reliability of variograms, whose parameters were used in kriging.

The goal of this study was to assess the probability of soil pollution on the basis of field measurements of magnetic susceptibility performed on the soil surface. Selected methods were used for the determination of the probability of soil pollution, namely IK, EBK, and indicator cokriging (IC). The initial z_k levels of κ were based on the results of previous studies carried out in the Upper Silesian Industrial Area (USIR) (Strzyszcz and Magiera, 1998; Magiera et al., 2007; Zawadzki et al., 2009). The main type of measurement used in this study was a surface measurement of κ. It was selected because it is a primary, fast, and easy-to-use measurement of potential soil contamination in soil magnetometry. Additionally, in order to validate the results, measurements of κ in the soil profile and chemical measurements were performed.

2. Material and methods

2.1. Study area

The study area was located in the eastern part of the USIR in southern Poland. The USIR covers more than 3000 km^2, within which a