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Short Communication

# Magnetic Susceptibility and Heavy Metals Distribution from Risk-cultivated Soil around the Iron–Steel Plant, China

Magnetic susceptibility is a non-conventional way that can be used for evaluating proxy soil heavy metals pollution. The paper monitors available heavy metals (Cu, Fe, Zn, and Mn) present in cultivated soils around iron–steel plant by soil magnetic susceptibility. Our study was located in an area with high pollution with small grid density of 250 m in China. Results showed that low field magnetic susceptibility was significantly correlated with available Cu, Zn, and Mn. No clear association exists between magnetic susceptibility and available Fe, soil organic matter, pH. Frequency dependent susceptibility >5% suggests the possible presence of super-paramagnetic particles, fly ashes produced during coal combustion.

**Keywords:** Coal combustion; Ecosystem safety; Pollution; Soil magnetic susceptibility; Soil management

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## 1 Introduction

Heavy metals in soils have recently received increasing attention [1–4]. Some soil heavy metals are physiologically essential for plants and animals, thus they have a direct or indirect impact on agricultural products and human health, and therefore they are closely related to ecosystem safety [5–7].

During the last few decades, many studies of the total content of heavy metals in urban areas have been reported [8–13]. Although the degree of pollution depends not only on the total heavy metal content, but also on the proportion of their mobile and bioavailable forms [3, 13–15]. It is more important to know the available content of soil heavy metal, for plants and agricultural products directly absorbed them [14–18].

It is possible to use easily measured magnetic properties to identify and trace heavy metal pollution in the environment. Measurements of low field magnetic susceptibility of surface soils have been applied recently around local pollution sources [9, 13–15]. Soil magnetic susceptibility is sensitive to presence of ferrimagnetic minerals [19–21]. Ferrimagnetics in soils are of both primary and different forms of secondary origin [4, 14–16]. Most important sources of anthropogenic ferrimagnetic particles include fly ashes produced during combustion of fossil fuel [17, 18, 22–27].

The aim of this work was to assess if available heavy metal contents (Fe, Cu, Mn, and Zn) in cultivated soils around iron–steel plants are correlated with magnetic susceptibility, in order to determine if magnetic susceptibility can be used as a quick and inexpensive method for detection of higher available heavy metal.

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**Abbreviations:** **CV**, coefficient variation; **SP**, super paramagnetic

## 2 Materials and methods

Soil magnetic susceptibility was measured using a Bartington MS2 susceptibility meter. By using a MS2B dual frequency sensor, both low- and high-frequency susceptibility were measured ($X_{LF}$ and $X_{HF}$), allowing the frequency-dependent susceptibility ($X_{FD}$) to be calculated:

$$X_{FD} = \frac{X_{LF} - X_{HF}}{X_{LF} \times 100\%}$$

The Linfen region is well known for intense coal mining and related heavy industry (steel–iron production and processing). The study area, located south of Shanxi Province, lies in longitude 110°22′–112°34′ and latitude 35°23′–36°57′. Prevailing soil types in the study area are brown soil and lime-brown soil.

Detailed magnetic investigation was carried out on 250 × 250 net of topsoil distributed around iron–steel plants. A total of 60 topsoil (0–20 cm) for the cultivated layer, where fly ash from steel mills and coal combustion are deposited were collected in October 2010. The samples were taken with a stainless steel trowel and stored in a plastic bag. The samples were air-dried at room temperature and sieved using a mesh-size of 2 mm. The available metal concentrations for Fe, Cu, Mn, and Zn were analyzed by flame atomic absorption spectrometry (AAS).

## 3 Results and discussion

### 3.1 Description of soil properties

The concentrations of the available heavy metals and soil magnetic susceptibility in the 60 topsoil samples are shown in Tab. 1. Low frequency magnetic susceptibility ($X_{LF}$) represents the total contribution of ferrimagnetic minerals. $X_{LF}$ values ranged from $71.5 \times 10^{-8}$ to $600.7 \times 10^{-8}\ m^3\ kg^{-1}$, mean values $X_{LF} = 130.79 \times 10^{-8}\ m^3\ kg^{-1}$ (Fig. 3).

 

**Table 1.** Descriptive statistics of soil properties

| | Minimum | Maximum | Mean | Median | SD | Variance | Skewness | Kurtosis | CV |
|---|---|---|---|---|---|---|---|---|---|
| pH | 7.04 | 8.96 | 7.84 | 7.84 | 0.26 | 0.066 | 0.38 | 7.49 | 3.27 |
| OM (%) | 0.30 | 5.24 | 2.77 | 2.63 | 0.76 | 0.58 | 0.54 | 2.78 | 27.32 |
| $X_{LF}$ ($10^{-8}$ m$^3$ kg$^{-1}$) | 71.5 | 600.70 | 130.79 | 98 | 104.60 | 10941.18 | 3.59 | 12.61 | 79.98 |
| $X_{HF}$ ($10^{-8}$ m$^3$ kg$^{-1}$) | 67.80 | 595.30 | 125.25 | 93.1 | 104.34 | 10887.61 | 3.59 | 12.62 | 83.31 |
| $X_{FD}$ (%) | 0.89 | 8.69 | 5.17 | 5.75 | 1.80 | 3.25 | −0.52 | −0.39 | 34.82 |
| Cu (ppm) | 0.52 | 1.89 | 1.04 | 1.01 | 0.31 | 0.09 | 1.85 | 6.20 | 29.96 |
| Zn (ppm) | 1.36 | 8.12 | 3.85 | 3.81 | 1.96 | 3.82 | 1.05 | 1.73 | 49.26 |
| Fe (ppm) | 3.35 | 20.86 | 6.08 | 5.48 | 2.74 | 7.49 | 3.54 | 15.31 | 45.05 |
| Mn (ppm) | 4.89 | 14.46 | 8.66 | 8.46 | 2.19 | 4.82 | 0.69 | 0.32 | 25.35 |

The values lie within the range commonly observed in related soils. $X_{FD}$ is sensitive to the presence of super paramagnetic (SP) grains. The 83.3% $X_{FD}$ values >3% in study areas prove that the magnetic properties are controlled by the presence of SP grains. The lower values point to the additional presence of multidomain (MD) particles. The high mean values $X_{FD} = 5.17\%$ indicated that samples contain SP grains. In such case, apparently high frequency-dependent susceptibility may be an artificial fact, resulting from coal-burned processing.

Available copper concentration values vary between 0.52 and 2.44 ppm. Concentrations of available Zn, Fe, and Mn were found to be 1.36–11.17, 3.35–20.86, and 4.89–14.46 ppm, respectively.

The coefficient variation (CV) values of soil properties in the study ranges from 0.03 to 0.83, indicating that they had strong variations. The CV of $X_{LF}$ and $X_{HF}$ were 0.80 and 0.83, respectively, suggesting that $X_{LF}$ and $X_{HF}$ have the greatest variation. We can infer that the surface soil magnetic susceptibility may be influenced by steel plant activities such as steel mills and coal burning. The CV of available heavy metals was between 0.25 and 0.49, suggesting that they had a moderate variation.

The content of organic matter is about 0.3–5.24%. The mean value is 2.77%. These are relatively high values compared to other soils from the same climatic zone. The importance of organic matter for the formation of fine grained magnetite/maghemite in soil has been observed by several authors. According to the pH data available, all the studied soils are alkaline (pH varies between 7.04 and 8.96). At higher pH, $Fe^{2+}$ adsorption increases due to increasing amounts of positively charged $Fe(OH)^{2+}$ species [16–20]. High pH is favorable for magnetite formation.

Spatial distribution of surface magnetic susceptibility of the study area is outlined as in Figs. 1 and 2. The change in magnetic susceptibility values as dependence on their distance from the plant is shown. The highest value of magnetic susceptibility is near the plant

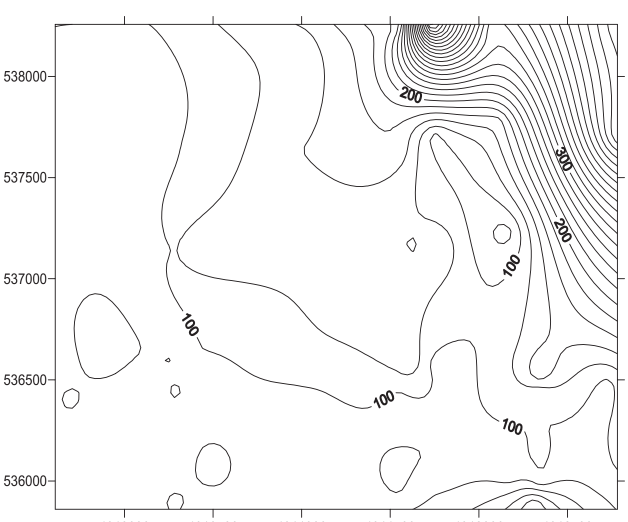


**Figure 1.** Contour plots of spatial distribution of soil low frequency susceptibility.

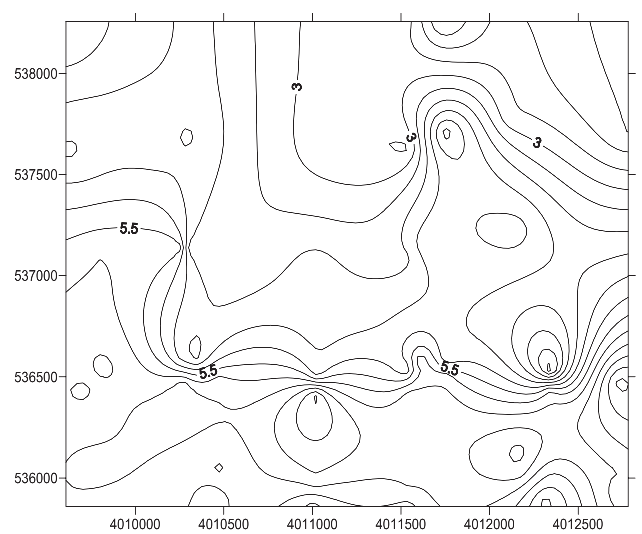


**Figure 2.** Contour plots of spatial distribution of soil frequency dependent susceptibility.

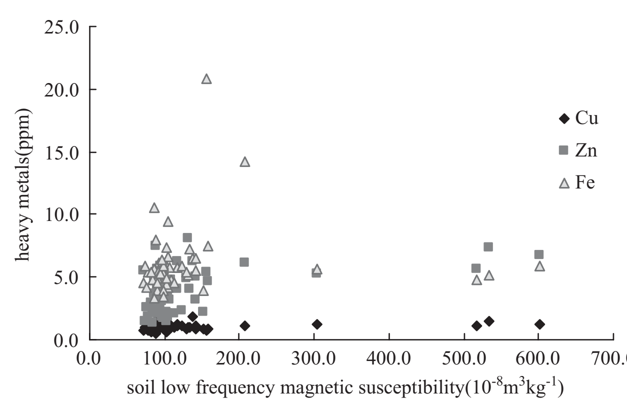


**Figure 3.** Scattered plots displaying the relationship between soil low frequency magnetic susceptibility and heavy metals content.

 

**Table 2.** Correlation coefficients between available heavy metals and magnetic susceptibility

| | PH | OM | $X_{LF}$ | $X_{HF}$ | $X_{FD}$ | Cu | Zn | Fe |
|---|---|---|---|---|---|---|---|---|
| OM (%) | −0.116 | | | | | | | |
| $X_{LF}$ ($10^{-8}$ m$^3$ kg$^{-1}$) | 0.103 | 0.145 | | | | | | |
| $X_{HF}$ ($10^{-8}$ m$^3$ kg$^{-1}$) | 0.105 | 0.146 | 1.00** | | | | | |
| $X_{FD}$ (%) | −0.252 | −0.177 | −0.666** | −0.673** | | | | |
| Cu (ppm) | 0.039 | 0.235 | 0.272* | 0.266 | 0.117 | | | |
| Zn (ppm) | 0.130 | 0.226 | 0.453** | 0.452** | −0.347** | 0.558** | | |
| Fe (ppm) | 0.242 | 0.082 | 0.064 | 0.066 | −0.272* | 0.155 | 0.325* | |
| Mn (ppm) | −0.302* | 0.080 | −0.315* | −0.317* | 0.269* | 0.121 | −0.043 | 0.086 |

Notes: *indicates $p < 0.05$; **indicates $p < 0.01$.

and to the south. Higher values of magnetic susceptibility were found at the reference point in this direction. This is due to prevailing wind erosion.

## 3.2 Correlation with available heavy metals

Table 2 shows the Pearson correlation coefficients between magnetic susceptibility values and available heavy metal concentrations for all analyzed samples. Low frequency magnetic susceptibility ($X_{LF}$) shown a significant positive correlation with available Cu ($r = 0.272$), Zn ($r = 0.453$), and negative correlation with available Mn ($r = -0.315$) levels. While frequency magnetic susceptibility ($X_{FD}$) showed a significant negative correlation with available Zn ($r = -0.347$) and positive correlation with available Mn ($r = -0.269$).

The Pearson correlation value between available Cu and Zn (Tab. 2) shows a linear correlation suggesting the same pollution source. Zn is not of typically lithogenic origin. It can be found in topsoils due to high mobility affected by specific industrial sources. This result is particularly interesting because these metals are representative of the pollution sources in the monitored area (Fig. 3). The magnetic susceptibility and available Fe are not significant. Contrary to Cu, Zn, Mn, and Fe plays as elements of typically lithogenic origin. Fe is characterized by variable efficacy of leaching methods. High $Fe^{2+}$ supply, organic matter, locally anoxic microenvironment is necessary to form magnetite. In conclusion, the obtained results suggest that magnetic susceptibility measurements can be used to monitor this kind of areas.

Soil magnetic susceptibility has shown no significantly correlation with organic matter and pH. This paper presents the results of a similar study to Yang et al. [18]. Comparison of data with others highlights some remarkable differences [15, 20–22]. The difference is our study sample coming from cultivated soil not urban street dust. This lack of correlation can be attributed to high pH values, intense fly ash particles, and from coal combustion in cultivated soil.

## 4 Conclusions

The magnetic susceptibility values decrease with their distance from the source of contamination. The highest $X_{LF}$ is $600.07 \times 10^{-8}$ m$^3$ kg$^{-1}$, and located near steel–iron plant. Available heavy metal concentrations in the analyzed samples and the correlation coefficient indicate a common source for Zn and Cu with an industrial contribution [1, 4, 7–11, 22, 27].

We found in this horizon industrial fly ash in the size of SP-particles. A major problem in the investigation was the influence of human activities. The industrial particles cover the original soil signal in the topsoil and the homogenization by the cultivation make it possible to observe soil pollution processes [14–27].

We believe that from the correct interpretation of magnetic susceptibility data, it is necessary that we should have a careful analysis of the tested site and the integration between magnetic susceptibility data and chemical observations [17–25]. More detailed work is under way for providing more reliable magnetic susceptibility system for the contaminated soils.

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