Spatial variability of soil magnetic susceptibility under different scales: a case study of Xiangtan

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Abstract. The characteristics of soil magnetic parameters can reflect the natural environment evolution and the human activities influence. By systematically sampling and measuring the sediments and onshore soils in representative water of Xiangtan City, spatial estimation was carried out by Kriging Spatial Interpolation with the help of SPSS, ArcGIS, Surfer, and other statistical and spatial analysis software. The results showed that: (1) Under the city scale, the spatial variation of soil magnetic susceptibility was large and ranged from $1.167 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ to $165.93 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$; (2) the soil magnetic susceptibility varies greatly under different land-use patterns, which may be related to the accumulation and absorption of magnetic substances in the soil environments. On the functional area scale, human activities on soil magnetic susceptibility were relatively large, which might be closely related to agricultural activities and domestic waste discharge; (3) the distribution of soil magnetic susceptibility was mainly affected by various factors; (4) the spatial autocorrelation distance decreased from the city scale to the functional area scale. Structural elements, such as sedimentation, topographic gradient, animals and plants, have a more significant influence on the spatial distribution of soil magnetic susceptibility.

1. Introduction

The surface layer of soil is the concentrated place most affected by various human activities. For example, fuel combustion, metal smelting, traffic exhaust, and domestic waste often produce massive magnetic particles, which enter the soil and sediment in various forms, resulting in a magnetic enhancement of soil [1]. This indicates that soil magnetism is susceptible to exogenous influences. The endogenous source of soil magnetism mainly refers to the secondary magnetic minerals formed by the chemical or biochemical action of "primary" iron [2]. Soil magnetic susceptibility is the most common soil magnetic parameter, which refers to the ratio of the induced magnetization and the magnetic field intensity generated by the soil in a weak external magnetic field. It reflects the difficulty of soil magnetization and the magnetic field strength [5, 6]. Previous studies showed the soil parent rocks, weathering degree, climatic conditions, geological conditions, hydrological conditions, and soil development degree had an important impact on soil magnetism [3]. The magnetic properties of lake sediments and onshore soil well record the natural environment and human activities [4].

Hoffmann et al. studied the magnetic susceptibility of the soil on both sides of the road. The results showed the high magnetic susceptibility of the surface soil expressed a zonal distribution along expressway [7]. Li Shan et al. believe that the magnetic anomaly enhancements of surface soil in Jiading District of Shanghai were related to the release of numerous magnetic particles from industry.
and traffic. The spatial distribution of land-use had a significant influence on the spatial distribution of the magnetic properties of surface soil [8]. The study of Shenyang New Town showed the magnetic susceptibility of agricultural land was higher because of the influence of the fertilization, irrigation, and planting. The change of magnetic susceptibility of Napahai Lake in Yunnan was strictly related to the dynamic and sedimentary environment [9].

At present, most research on the multi-scale spatial variability of soil magnetic susceptibility focused on large cities. Li Jing et al. found the spatial correlation of soil magnetic parameters would increase with the shrinkage of spatial scale and the content of soil magnetic minerals was higher in areas where human activities were frequent, such as roads, entrances and exits, and industrial zones [1]. This study established three scales spatial structure models and spatial interpolation to improve the prediction accuracy. Zeng Liting et al. used the factor Kriging method to analyze the spatial magnetic susceptibility of surface soil in Xuzhou. Their results showed that the magnetic susceptibility of soils at the local scale was significantly affected by industry, agriculture and transportation, but under the regional scale, it was dominated by natural factors [10]. Taking part of the water area of Xiangtan City as the research object, this paper explored the spatial magnetic susceptibility variability of soil at different scales (i.e., the city scale, functional scale, and the inner scale of sample area) and the influencing factors. This study can provide the basic data for the environment monitoring of water and atmosphere, and soil restoration.

2. Research area
Xiangtan City is relatively high in the north, West and south, and is slightly flat in the East and the West. Its topographic types are diverse, mainly a typical low mountain and hill. Xiangjiang is located in the eastern part of the city, and its main tributaries are Juanshui River and Lianshui River. The climate of Xiangtan belongs to a subtropical monsoon humid climate with abundant precipitation, sufficient solar and thermal resources. The average annual precipitation is about 1200-1500mm, and the rainfall occurs in April - July.

Xiangtan's geographical position is superior. Many expressways and railways meet and pass here, which is highly beneficial to economic development. Xiangtan, together with Changsha and Zhuzhou, is the "Golden Triangle" urban agglomeration with the most developed politics, economy and culture in Hunan Province [11]. In recent years, Xiangtan's economy has been growing, and its main industrial types include coal, metallurgy, chemical fiber, chemical industry, textile, leather, agricultural products' processing, etc.

3. Materials and methods
In March 2018, samples were taken from Yuhu Park, Juhuatang Park, ponds along Liancheng Avenue, ponds of Shuiku Village, the pond at the Backstreet of Hunan University of Science and Technology (HNUST) and Juhua Lake (Figure 1). The samples covered different areas of the city, suburbs, and villages. Positioning with Global Positioning System (GPS), 75 representative samples were collected and sealed in polyethylene bags.

In the laboratory, picked up the litter, plant roots, gravel, and other debris and dried naturally. Later, the samples were dried in the oven for 48 hours at 105°C. Take out the dried soil samples and mix them evenly. Then, grind the samples through 100 meshes sieve by using agate mortar. The soil magnetic susceptibility was tested by Bartington MS2. After repeated measurement three times, calculated the average value.

Kriging is one of the principal methods of geostatistics. It considers the relationship between the sample points and the structural characteristics, predicts the unknown regional values according to the known regional values, and uses optimal unbiased estimation to simulate the spatial distribution of geographical phenomena. The formula for ordinary Kriging is:

\[ Z(x) = \sum_{i=1}^{n} \lambda_i Z(x_i) \]
In the formula, $\lambda_i$ is the weight coefficient, $\sum_{i=1}^{n} \lambda_i Z(x_i) = 1$ is determined by the semi-variogram, and $n$ is the number of sample points, $Z(x)$ is the estimated value of the actual value. This study utilized ArcGIS, Surfer, and SPSS to analyze.

![Figure 1. Schematic map of the sampling area.](image)

4. Results and discussion

4.1. City scale

On a city scale, the magnetic susceptibility ranges from 1.167 m$^3$kg$^{-1}$ to 165.93 m$^3$kg$^{-1}$. Its standard deviation, variance, kurtosis, the skewness and coefficient of variation is 35.878, 1287.22, 1.903, 1.24 and 0.769, respectively. Magnetic susceptibility values were to the right of the average value, and the top was slightly steep (Table 1).

| Number | Full distance | Minimum value | Maximum value | Mean value | Standard deviation | Variance | Skewness | Kurtosis | Coefficient of variation |
|--------|---------------|---------------|---------------|------------|--------------------|----------|----------|----------|------------------------|
| Magnetic susceptibility | 75 | 164.763 | 1.167 | 165.93 | 46.656 | 35.878 | 1287.22 | 1.24 | 1.903 | 0.769 |

4.2. Functional area scale

In this study, Yuhu Park and Juhuatang Park were classified as a residential area, while ponds along Liancheng Avenue, Shuiku Village and Backstreet ponds of HNUST were classified as an agricultural area. The soil magnetic susceptibility of the residential area is relatively high, and the average value is 69.037. The data distribution is to the right of the average value, and the top is steep. The average soil magnetic susceptibility in the agricultural area is 45.114 (Table 2). The data distribution is slightly to the left of the average value, and the top is slightly flat. The two subdivisions belong to strong variation.

The data of the two functional areas conform to a normal distribution. By using an exponential model for the residential area, the value of the nugget, sill, range and nugget/sill is 0.71, 1.089, 0.00184 and 0.652, respectively. For the agricultural area, the spherical model was used and the value of the nugget, sill, range and nugget/sill is 0.735, 0.995, 0.00145 and 0.739. The results showed that the soil magnetic susceptibility of the two functional areas belonged to a moderate spatial correlation,
small spatial autocorrelation distance, and moderate spatial variability. At this scale, different land-use patterns and soil environments lead to different accumulation and absorption of magnetic substances. Agricultural activities and domestic waste emissions may be the main reasons in this functional area. Undoubtedly, the difference of soil magnetic susceptibility between the functional areas is also huge under this scale.

Table 2. Descriptive statistical characteristics of the city scale and each functional area.

|                        | Total range | Minimum value | Maximum value | Mean value | Standard deviation | Variance | Skewness | Kurtosis | Coefficient of variation |
|------------------------|-------------|---------------|---------------|------------|--------------------|----------|----------|----------|-------------------------|
| Residential area (n=25)| 130.2       | 25            | 155.2         | 69.037     | 36.249             | 131.99   | 1.022    | 0.246    | 0.525                   |
| Agricultural area (n=21)| 58.07      | 17.47         | 75.53         | 45.114     | 16.897             | 285.51   | -0.21    | -0.956   | 0.375                   |

4.3. Inner scale of each sample area

From Table 3, the soil magnetic susceptibility of Yuhu Park and Juhuatang Park is high, and the degree of dispersion is huge. The soil magnetic susceptibility of Backstreet of HNUST, the vicinity of Liancheng Avenue and the Shuiku Village was moderate, while that of Jiuhua Lake was low. The variation coefficient of Yuhu Park, Juhuatang Park, Backstreet of HNUST, ponds of Shuiku Village and Jiuhua Lake is 57.15%, 48.92%, 44.64%, 38.38%, and 98.14%, respectively. The variability of magnetic susceptibility in each area was significant, uneven and high variability.

One surface soil sample and one bottom mud sample were collected from the ponds beside Liancheng Avenue. The magnetic susceptibility was moderate. This is due to the effective management of soil and water by the local government, which makes it difficult for magnetic materials to migrate downward or accumulate [12].

The Backstreet of HNUST is next to the Shanghai-Kunming Expressway and surrounded by farmlands. The magnetic susceptibility is high, which should result from more traffic pollution, domestic waste and other waste piled up.

The soil magnetic susceptibility of the two ponds on the south side of the road is lower than that of ponds on the north side of the road. This condition has a great relationship with their different environment. The ponds on the north side of the road are closer to Hurui Expressway, its soil is more easily affected by the road dust and vehicle exhaust emissions. In addition, the sediments are also severely affected a steel plant in its northwest. Unlike the former, the two ponds on the south side of the road are typical farmland. Due to far from the traffic line and the factory, they are less affected by traffic pollution and industrial pollution. Meanwhile, repeated planting diluted the magnetic particles [12].

Table 3. Descriptive statistics of the city scale.

|                    | Total range | Minimum value | Maximum value | Mean value | Standard deviation | Variance | Skewness | Kurtosis | Coefficient of variation |
|--------------------|-------------|---------------|---------------|------------|--------------------|----------|----------|----------|-------------------------|
| Yuhu Park (n=18)   | 107.77      | 29.23         | 137           | 72.281     | 41.306             | 1706.18  | -1.61    | -1.265   | 0.571                   |
| Juhuatang Park (n=13)| 130.2    | 25            | 155.2         | 66.044     | 32.307             | 1043.76  | 1.77     | 4.575    | 0.489                   |
| Backstreet of HNUST (n=6)| 55.07  | 20.47         | 75.53         | 47.828     | 21.351             | 455.878  | .022     | -1.854   | 0.446                   |
| Liancheng Avenue (n=2)| 2.57   | 47.6          | 50.17         | 48.884     | 1.8151             | 3.295    | —        | —        | —                       |
| Shuiku Village (n=13)| 51.03    | 17.47         | 68.5          | 43.282     | 16.612             | 275.942  | -0.67    | -1.073   | 0.384                   |
| Jiuhua Lake (n=23)| 54.7       | 1.17          | 55.87         | 14.344     | 14.077             | 198.171  | 1.621    | 2.554    | 0.981                   |

Samples from Yuhu Park, Juhuatang Park, and Jiuhua Lake were analyzed to better understand the spatial variability of soil magnetic susceptibility under the inner scale of the sample area (Table 4). The simulation results showed the soil magnetic susceptibility of the three places was a moderate spatial correlation.
The soil magnetic susceptibility of Zhonghu Lake of Yuhu Park is high. The reason is there had bars and water motorboats in this area. These entertainment facilities and place would release substances containing certain magnetic particles in the way they run their businesses [13]. Recently, the park has carried out building maintenance. Building materials and fly ash also contributed to the increase of magnetic susceptibility [14]. Furthermore, because Yuhu Park is located in the central of the city with huge traffic volume, vehicle exhaust emissions, friction between vehicle and road surface and road dust will lead to the increase of magnetic particles [15]. However, a large area of low values appeared on the west side of the lake, indicating that the soil magnetic susceptibility near the center of the lake was relatively low. This situation is related to less human activities.

Soil samples in the Juhuatang Park were collected from two lakes, including a big lake and a small lake. For the small lake, its soil magnetic susceptibility has an apparent high-value center, which is related to its environment and human activities. Specifically, the main reasons are: (a) the action of early building repair, gasoline racing, barbecue and other leisure activities have an inevitable impact on the increase of soil magnetic susceptibility; (b) because there is a moving platform in the lake center, a large number of tourists are willing to go to the platform and play a lot of water entertainment. This situation will lead to the magnetic particles accumulation. Moreover, the smaller size of the lake makes the agglomeration effect stronger; (c) although the small lake has considerable biomass and a large number of ornamental fishes, the work of clearing the pond is not good, which may lead to the accumulation of magnetic substances [15]. The soil magnetic susceptibility of the larger lake is lower than that of the small lake. There are several visible low-value areas, while there is a relatively high-value area in the east. The change of high and low value relates to vegetation status, traffic flow, and biological factors.

Table 4. Descriptive statistics of magnetic parameters under the city scale.

| Model            | Nugget | Range (km) | Step  | Sill  | Nugget/Sill |
|------------------|--------|------------|-------|-------|-------------|
| Jiuhua Lake      | Exponential | 0.327     | 0.00173 | 0.00089 | 1.042      | 0.314       |
| Yuhu Park        | Gaussian | 0.696     | 0.00089 | 0.0006  | 1.219      | 0.57        |
| Juhuatang Park   | Exponential | 0.738     | 0.00317 | 0.00026 | 1.174      | 0.629       |

The high and low variation of soil magnetic susceptibility in Jiuhua Lake is mainly caused by the local natural environment and human activities. Overall, the magnetic susceptibility of the area is low. Because the study area is located in the newly built development zone, the surrounding construction density is still relatively low, and the interference time of industry and other human activities is short and few. The park greening is very good, and the new hybrid lawn is widely distributed. The typical wet environment near the lakeshore has more plants with developed roots and fast growth, which plays a certain role in reducing the absorption and transformation of magnetic substances [16]. The high-value area on the southwest side of the park is located at the exit and entrance of the park. Therefore, a large flow of people and vehicles releases massive magnetic particles in this area [1]. The center of the study area is a large area with low magnetic susceptibility due to less human activities. However, near the hydrophilic platform, trestle bridge, and gallery pavilion, the magnetic susceptibility of the soil was relatively high. In addition, the high magnetic susceptibility of Jiuhua Lake is mostly lakeshore grassland with a steep slope, which indicates that soil magnetism is affected by micro-topographic slope [17].

5. Conclusion
The soil magnetic parameters of bottom mud and onshore soil in Xiangtan showed that: (1) From the city scale, industrial and traffic conditions are important factors affecting the spatial heterogeneity of soil susceptibility. The soil magnetic susceptibility decreased gradually from the central city to the outside, and its spatial variation is significant. (2) From the functional scale, the average magnetic susceptibility of the residential area is bigger than that of the agricultural region. The land-use patterns have many effects on magnetic susceptibility, and the degree of adsorption and accumulation of magnetic substances in various soil environments is different. (3) From the inner scale of each sample
area, the soil magnetic susceptibility is high in Yuhu Park and Juhuatang Park, moderate in Liancheng Avenue, Shuiku Village and Backstreet of HNUST, and low in Jiuhua Lake. The magnetic susceptibility in each sample area is large and strong variation, showing a moderate spatial correlation.

Acknowledgments
Thanks to Liu Fengying, Li Ying, Zhou Ye, Wang Ruofei, Li Yingying and Zhang Xiaoliang for their work on this research.

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