GIS-technology for temporal-spatial analysis of mobile iron content in Southern Taiga soils

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Abstract

A method of landscape-guided interpolation is presented to compile maps of isoconcentrations using both analytical data and information from thematic maps, such as landscape, soil and other ones. The interpolation formula includes the weight of a concentration in each sampling point depending not only on the distance but also on the qualitative similarity with the point of interpolation as well. A case study on the mapping of the mobile Fe contents in southern taiga soils demonstrates the possibilities of the elaborated method. A series of maps presenting Fe spatial pattern in topsoils for 6 years was compiled. The relative importance of agents of Fe mobilization was determined by comparing their impact coefficients for the considered time period. The joint analysis of maps and meteorological information allowed to reveal the interannual dynamics character of mobile Fe.

1 Introduction

Traditionally the mapping of geochemical fields is based on the actual values of chemical element contents in a limited set of points and performed using methods of two-dimensional interpolation and extrapolation. Values of a geochemical parameter in cells of a regular grid are for this purpose calculated, then contours drawing is executed. The simulated parameter value $C(x,y)$ in a cell is calculated from interpolation formulae. The most popular formula - weighted mean:

$$C(x,y) = \frac{\sum\limits_{i=1}^{n} \phi(r_i) C_i}{\sum\limits_{i=1}^{n} \phi(r_i)} \tag{1}$$

where $\phi(r_i)$ is weight function, dependent on distance r_i, C_i is the parameter value $C(x,y)$ in i-th sampling point, n—number of sampling points. Most common weight functions are in inverse ratio to the distance r_i: $\phi(r_i) = \frac{1}{r_i}$ or its square $\phi(r_i) = \frac{1}{r_i^2}$.

Modeling of geochemical fields has some special features, complicating the interpolation and extrapolation of the geochemical data by conventional methods [6]:

1. Usially, the properties of a field being mapped are unknown *a priori*, there is possibly only the assumption concerning character of a field in local sites;
2. In most cases the sampling points are located in the survey area irregularly and some characteristic points can be missed;
3. Typically, the quantity of the samples is quite limited because field and laboratory works are very expensive and time-consuming;
4. Interpolation should result in unbiased estimation of concentration field, i.e interpolated values at the sampling points should should coincide with measured ones;
5. it is necessary to solve problems of both interpolation, and extrapolation at once.

The considered features are taken into account in special algorithms of mathematical-cartographic modeling, which can be amalgamated in two groups [5]. The first group of algorithms, which are widespread in Earth sciences, is applied the kriging [8]. This method is based on statistical properties of a spatial structure of individual parameters of geosystems. Variation of this method, called co-kriging, allows to take into account correllation between modelled parameter and several several others, but all of them must be quantitive.

Other group of algorithms combines the data in the sampling points with the information about bio- and lithogeochemical differentiation of landscape components, natural borders, relief etc. contained in landscape, soil or other maps. The combination of point measurements with the cartographic information essentially increases volume of the data, used at compilation of geochemical maps, and, hence, increases their accuracy. Algorithms of this group allow to establish quantitative relations between the parameter being mapped and a set of the physiographic characteristics and conditions and thus to develop spatial model.

The first experience of incorporating the information from soil map in process of interpolation was exhibited by Stein et al. [7]. In their paper soil map delineations are used to stratify the survey area, then each of the strata is separately kriged. Other method is developed for drawing up prognostic maps of quantitative soil and geochemical properties [4]. The predictive value of a soil parameter is taken as a weighted average of soil map prediction and prediction obtained from kriging the observations. The weights are chosen such that the accuracies of the individual prediction methods are taken into account. The proposed method was tested when mapping the mean highest water level in a Dutch polder area. Validation showed that combining the information from a

1:50,000 soil map with kriged map produces a more accurate map than when either the mentioned maps are used separately.

In the present paper a new method of automated typological interpolation of data is described. The so called landscape-guided interpolation takes into account not only the spatial position of the sampling points and the corresponding values of parameter being interpolated, but also the landscape differentiation of territory.

2 Method of landscape-guided interpolation

2.1 Basic assumptions and formulae

This method has been proposed for development of a digital geochemical field model. The method is based on the fact that there are several landscape factors influencing the distribution of the mapped parameter. The method applies the interpolation formula of weighted average 1. The well-known drawback of this formula is that each interpolated value depends on data for all sampling points. In our case this becomes an advantage because the widely separated points may have similar landscape characteristics and so they may have rather pronounced influence on the interpolated value. The method considers the differentiation of soil or landscape contours and evaluates the impact of landscape and soil-geochemical characteristics on the spatial distribution of chemical element concentrations. Thus the weight coefficients in the interpolation formula depend not only on the distance but also on its qualitative similarity between the sampling point and point of interpolation.

This can be viewed as interpolation in multi-dimensional space, where distance between point depends on both the spatial distance the point of interpolation and the distance in the space of a certain classification which accounts for the factors of differentiation. Here there is a problem to get agreement on the weights of qualitative and quantitative factors. The majority of available landscape geochemical classifications are not intended for such tasks, so they lack the techniques of calculating the qualification distances. That's why we choose the classification based on the system of conditions, each of them can be either present or absent at a certain point. These conditions can include, for example, the presence of a calcareous layer in soils, the degree of podzolization, etc. The information of landscape, soil and other maps of this kind is usually classified with more than two variants at each level. However it is rather simple to express it in the form of "present or absent in a given area" (concerning a certain type of vegetation, soil- or relief-forming processes, etc.).

The weight coefficients for each of these conditions, or factors, are not known beforehand and should be estimated from the sampling data.

We have used following interpolation formula:

$$C_k = \frac{\sum_{i=1}^{n} \left[C_i \left(a_0 + \sum_{j=1}^{m} a_j \lambda_{jki} \right) \phi(d_{ik} \right]}{\sum_{i=1}^{n} \left[\left(a_0 + \sum_{j=1}^{m} a_j \lambda_{jki} \right) \phi(d_{ik} \right]} \tag{2}$$

where C_i is the geochemical parameter value at the i-th sampling point, $i = 1, \ldots, n$, d_{il} is spatial distance between interpolation point k and sampling point j, $\phi(d)$ is a weight function of distance: $\phi(d) = \frac{1}{d}$, a_j are weight coefficients of condition j, $j = 1, \ldots, m$, a_0 is so-called background coefficient, λ_{jki} equals 1 if j-th condition is the same in points i and k and zero otherwise.

Weight coefficients a_j are estimated using least square method by minimizing sum:

$$\sum_{i=1}^{n} \left(C_i^{\mathrm{mes}} - C_i^{\mathrm{int}} \right)^2 \rightarrow \min \tag{3}$$

where C_i^{mes} is concentration, measured in the i-th sampling point and C_i^{int} is the concentration interpolated for this point using formula 2 from all sampling point but it itself.

The values of calculated weight coefficients a_j have substantial meaning: the greater is the coefficient the stronger is the influence of the given factor on the mapped parameter. The values of all factors lie within the same range between 0 and 1, so relative their significance can be analyzed by comparing the weight coefficients. Therefore the weight coefficients calculated according to this method were called the influence coefficients.

2.2 Examples

The application of the described method can be illustrated by several examples of situations typical for geochemical surveys (fig.1,2). For each of them the landscape map (a) is presented which was the basis for selecting the factors of differentiation; all sampling points are indicated on this map with corresponding values of concentrations. The maps of isoconcentrations compiled by direct interpolation (b) and by landscape-guided interpolation (c) are also presented.

First illustrate the interpolation in the case when there are two types of complex-shaped areas, i.e. a valley within a uniform plain surface (fig. 1). Only one condition, namely the location of a point within or out of the watershed area, was used for interpolation.

In the case of plain-valley situation there is the only one landscape-geochemical transect with sampling points on the studied territory. This is evidently inadequate to show the real pattern of concentration field if the direct interpolation is used. Fig.1b proves this. The method of landscape-guided interpolation (fig.1c) allows to distinguish the main feature of concentration field, i.e. the difference between valley and plain concentrations, even through the single transect

1.— plain, 2.— valley

Figure 1: The interpolation in the case of plain cut by valley .

1.— forest on podzolic soils. 2.— forest on grey forest soils. 3.— arable land on podzolic soils 4.— arable land on grey forest soils.

Figure 2: The interpolation with two factors

observations. It was supposed that differentiation between the valley and the plain is completely due to the single condition which was selected. If the researcher is not certain about the selection of condition it is advisable to have not less than 10 to 15 sampling points. By analyzing the impact coefficients one can become sure that the given condition of differentiation is really important.

Fig. 2 illustrates more complex situation. There are four polygons and two factors of diffeneciation—land cover and soil type. Only three of four polygons was sampled— both forest ones (1 and 2) and arable lands on grey forest soils (4). This is example of extrapolation, based on qualitive landscape properties.

It can be concluded from data values that both factors increase concentration and soil type has more influence than vegetation cover (average concentration in polygons with same soils are 3.5 and 5.75, while averages in forest polygons on different soils are 5.75 and 10.0). So the concentration in 3-rd polygon should be greater than in 1-st, but less than in second.

Analysis of influence coefficients shows that both factors have significant influence on concentrations (1.37— soils and 1.28— land cover).

Fig 2 shows that while direct interpolation is unable to distinguish between

Table 1: Data values and influence coefficients in example 2

	factors			Measured concentrations	
Polygon	Forest	Podzolic soils	Background coefficient	at sampling points	average
1	+	+	+	12.0 8.5	10.25
2	+	-	+	6.0 5.5	5.75
3	-	+	+		
4	-	-	+	3.0 4.0	3.5
Influence coefficients	1.279	1.365	0.558		

polygons 3 and 2, showing only general trend from 4 to 1, results landscape-guided interpolation are very close to qualitive analysis of situation, given above.

2.3 Limitations

The proposed method has also several limitations.

First, if the set of selected conditions doesn't represent the factors of differentition which are not always known a priori, then the quality of resulting map will not exceed that of direct interpolation.

Second, the number of sampling points should be 3–5 times that of conditions, otherwise the method gives unstable estimates of weight coefficients.

Third, the proposed method requires more complex calculations than the direct interpolation. This is to a certain extent compensated by calculation of influence coefficients which provide a researcher with useful information.

3 A case study

3.1 Study area and materials

To test the method of landscape-guided interpolation the modeling of temporal-spatial variations of mobile Fe contents in southern taiga soils was carried out. Undisturbed soils of the Smolensk-Moscow Upland have been chosen as the object of study. The study was executed at the experimental-teaching station of the Faculty of Geography, Moscow State University, located in the Kaluga district. This area has physiographic conditions typical for Non-Chernozemic centre of the Russian plain, it represents an undulating moranic plain, composed of loesslike mantle loams, with moderately continental climate and periodical excess of moisture. The soils of the study area have been roughly grouped into: soils of interfluves and weak slopes — sod-podzolic, gleyed and non-gleyed; soils of steep slopes — humus-accumulative on loamy deluvium and rendzinas on limestone outcrops; alluvial, gleyed and non-gleyed, of the upper floodplain and bog—low moor soils in depressions [1].

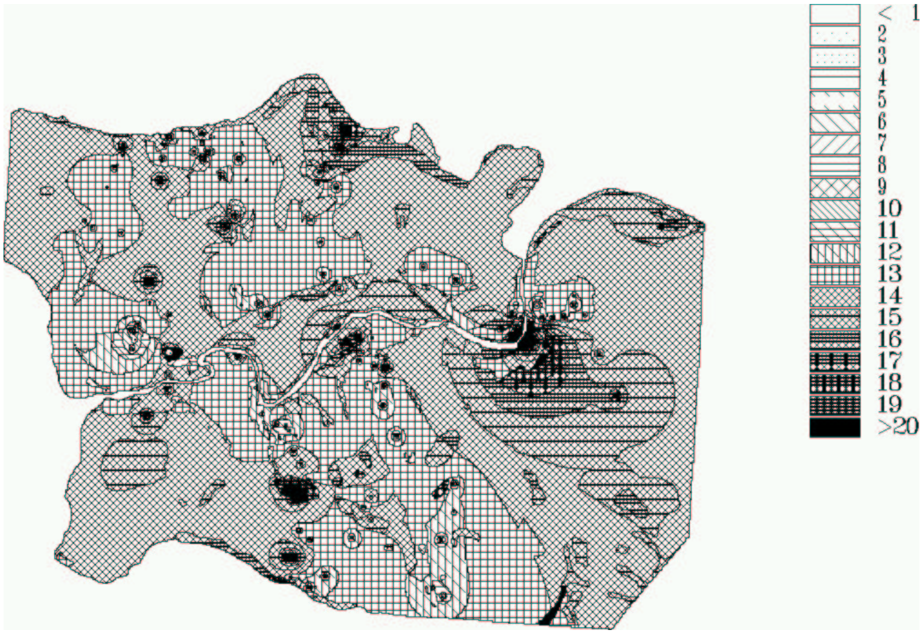

Figure 3: The maps of mobile iron concentrations (mg/100g) in topsoils for 1991

Data used include concentrations of easily mobile iron extracted by 0.1n H_2SO_4 and morphological descriptions of about 1100 soil profiles obtained every July during 1989–1994. The concentrations of Fe extracted by sulphuric acid characterize the amount of organomineral and ionic forms of mobile Fe caused by soil hydrothermic regime. According to Zaidelman (1965), the content of these easily mobile forms of Fe indicates the intensity of gley process in topsoils.

The information was systematized in the local geoinformation system. In the process of compiling Fe concentration maps the digital soil map, scale 1:10,000, was involved as well. The map in raster format consists of 563x688 squared cells. The original paper variant of the map was compiled by M.I. Gerasimova and I.P. Gavrilova. The software includes the database management system Paradox, version 4.0, and GIS package EPPL7, version 2.1. Software, developed by authors, which implements landscape-guided interpolation and process EPPL7 data files, is available via Internet at `http://www.ice.ru/~vitus/geography/loi`

3.2 Mapping

A series of maps presenting Fe spatial pattern in topsoils for 6 years was compiled using concentrations of mobile Fe measured in a number of points within the study area, digital soil map and Boolean array containing the information about the Fe differentiation factors in each unit of the soil map. The latter ones

Figure 4: The maps of mobile iron concentrations (mg/100g) in topsoils for 1994

refer to landscape and geochemical parameters which can influence the mobile Fe content in topsoils. In our case they are: soil-forming rocks (mantle loams, calcareous rocks, alluvium), vegetation (coniferous forest, low moor), content of organic matter (low or high), gley features in soil profile and pH of soil solution. These 9 agents of Fe mobilization were taken into account by means of Boolean array with values TRUE if this or another qualitative feature of soil or landscape is exposed in a given point and FALSE if they are not. The amount of sampling points varies each year from 100 to 160.

The significant dynamic of mobile iron content during study period was discovered. The maps for 1989 and 1990 show very low content of mobile Fe (the background concentrations were below 5 mg/100g) in all types of soils. Only the isolated spots of increased Fe concentrations stand out against the low background contents. They are situated in depressions, lower parts of erosion network and fragments of Protva floodplain. The 1991 displays more complex pattern of concentration field and the highest Fe concentrations everywhere fig 3. The background concentrations are 13-14 mg/100g, some areas having mobile Fe content above 20 mg/100g.

The 1992 has mean Fe concentrations about 10–11 mg/100g, the next 1993 is peculiar by increase of these values. The separate areas with maximal Fe concentration are expanded and captured the main parts of floodplains and bottoms of ravines. In the 1994 the background concentrations remain about 10-11 mg/100g (fig 4).

Table 2: Factors of Fe mobilization and their influence coefficients

Landscape and geochemical factors	Impact coefficients					
	1989	1990	1991	1992	1993	1994
weakly acid/ acid pH	-1.0	-3.9	0.45	-0.45	-1.05	0.26
alluvium	0.57	-1.17	0.03	0.88	4.05	-0.69
low humus content	-0.42	-0.7	-0.21	-3.97	-0.43	0.62
mantle loams	0.15	2.44	0.20	-1.05	1.21	0.26
raw humus	0	-1.15	0.78	1.63	0.39	0
low moor	-0.07	0.60	-1.45	-0.82	0.87	-0.14
calcareous rocks	0.35	-0.7	0.66	-0.37	1.67	-0.24
coniferous forest	0	1.72	-0.38	-0.65	0.39	0
gley features	0.15	0.08	0.86	-1.01	-0.77	-0.20

Although in each type of soils the concentration values are not constant, the soil types form a stable sequence with decreasing mean Fe concentrations [2]. On all the maps bog soils are distinguished for the highest concentrations. This phenomenon is explained by alternating redox conditions and by location of soils in depressions, where iron compounds get accumulated. The lowest contents of Fe in rendzinas are in good agreement with soil properties unfavourable for Fe mobilization. Rather unexpected were high values for alluvial soils with their weakly alcaline reaction and oxydative regimes dominant. They may be attributed to elevated humus content in these soils and to allochtonous enrichment alluvium with Fe. As for pairs of gleyed and non-gleyed soils - gley phenomena are thought to account for higher concentrations.

Results

The spatial differentiation of mobile Fe concentration can be related to the influence of agents of Fe mobilization. Analysis of impact coefficients for the considered time series (table 2) allowed to evaluate the their relative importance.

In our case the mobile Fe content is controlled first of all by pH, then by the factors responsible for the oxidation-reduction regime of the soils: soil-forming rocks with essentially different geochemical position and texture— alluvium and mantle rocks. The third group of acting agents comprises the biotic ones, namely low humus content, row humus and low moor with specific organic matter. These factors reflect the variety in the composition and the amount of organic matter existing in studied soils.

The mentioned factors have the largest absolute values of impact coefficients and stable sign indicating their effect on Fe behaviour. The established relationships are in accordance with the results received earlier [3]. These authors studied the distribution of different forms of iron in a waterlogged soil. They found out that increases in water soluble and exchangeable iron were favored by a decrease in both redox potential and pH.

To reveal the interannual dynamics character of mobile Fe the joint analysis of maps and meteorological information was performed. The latter comprised mean monthly air temperatures for the warm period and total annual precipi-

Table 3: The mean air temperatures for the warm period (III-VII) and annual precipitation at the Maloyaroslavetz meteostation and their deviations from the standard

Meteoparameter	Climatic standard	Mean for 1989–94	1989	1990	1991	1992	1993	1994
Temperature $T^\circ C$	9.5	10.4	12.1	10.2	11.2	10.6	10.2	9.8
Deviation ΔT		+0.9	+2.6	+0.7	+1.7	+1.1	+0.7	+0.3
Precipitation h,mm	646	722	705	902	756	489	746	714
Deviation Δh		+76	+59	+256	+110	-157	+100	+68

tation at the Maloyaroslavetz meteorological station (table 3).

The comparison the meteoinformation with cumulative curves (fig.5) depicting the distribution of areas with different mobile Fe contents showed the absence of direct correlations between the considered parameters. Nevertheless, it is obvious that the Fe concentration fluctuations are caused by soil water regime and water supplies in soil-ground layers related to weather conditions. It is known that water accumulation in soils and underlaying rocks depends not only on current weather conditions but also on surplus of water in the preceding period.

Minimum iron levels in 1989–90 were observed under the close to standard precipitation and increased air temperatures enhancing the evaporation of soil water. Maximum iron levels were formed in 1991 under slightly increased precipitation supposedly on the significant previous moistening. The following 1992 was peculiar by minimum precipitation. But rather high concentrations of mobile Fe caused by previous water supplies remain in soils. So, the alternation of wet and dry conditions in the 1992–94 results in the smoothing over the fluctuations in mobile Fe contents in topsoils.

Hence, mobile iron contents as well as water regime of soils is rather inertial parameter, especially for hydromorphic soils, which displays not only the hydrothermic conditions of the current year but also some previous ones. The more detailed description of trends could be achieved when time series data sufficient for statistical analysis will be gathered.

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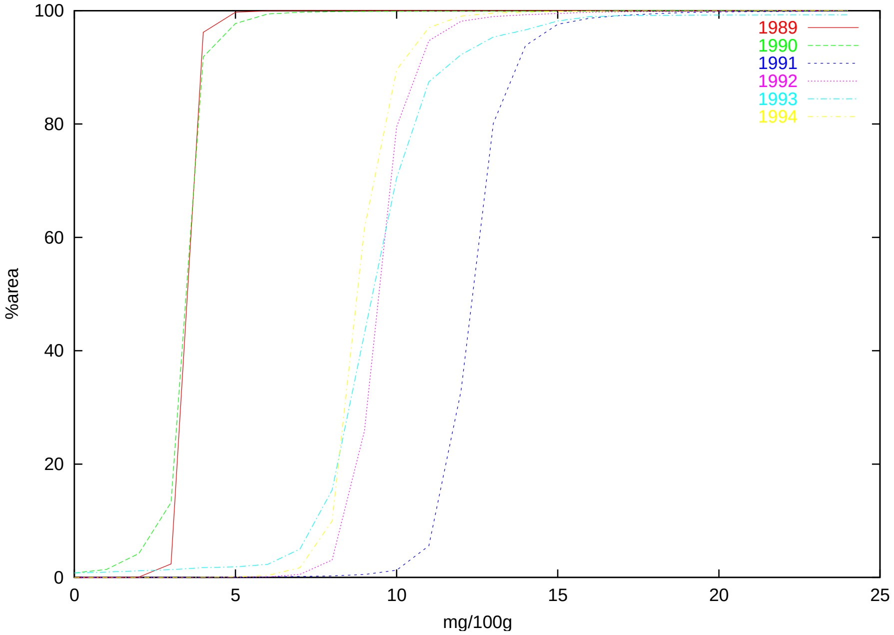

Figure 5: The cumulative curves

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