The Informativeness of NDVI in Studying the Patterns of Spatial Variation of Magnesium Content in Soils and Plants

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Abstract. The informativeness of NDVI of oat-pea mixture for predictive mapping of magnesium content in soils and plants has been examined. In regression models, NDVI has explained 51% of variance in the content of exchangeable magnesium in soils and 26% of variance in the content of total magnesium in plants. On the basis of the models obtained and NDVI values calculated from the Landsat 8 image (30 m resolution) prognostic maps of the soil properties and plants have been developed. The article describes comparison of soil parameters on magnesium content calculated for the ploughed layer of arable soils differing in soil organic matter (SOM) content: with high (5-8%) and medium (3-5%) SOM content. In medium-SOM soils (agro-chernozems, agro-dark gray) compared with high-SOM agro-chernozems, a lower content of exchangeable magnesium (in 1.5 times) was established, while studied soils did not differ from each other in the content of total magnesium. It was not found correlation between the reserves of above-ground phytomass of oat-pea mixture and content of magnesium in plants and soils.

Keywords: exchangeable magnesium, soil organic matter, digital mapping, above-ground phytomass reserves, oat-pea mixture, magnesium in plants, Chernozems, Phaeozems.

1 Introduction

Magnesium is an essential macroelement in the mineral nutrition of plants, because it an integral part of chlorophyll, in which photochemical reactions are carried out. The shortage of magnesium inhibits of synthesis of chlorophyll, therefore the main external manifestation of this process – spotted chlorosis of leaves [1]. According to foreign studies [2], signs of magnesium deficiency in plants are found when it is contained in mature leaves less than 0.20% by dry weight, magnesium content in the range from 0.25 to 1.0% is considered sufficient, excessive or toxic – more than 1.5%. The content of total magnesium in soils ranges from 0.1 to 1% [3]. Total magnesium includes four forms: water-soluble, exchangeable, non-exchangeable and organic. The proportion of these forms by content of total magnesium in soils is 0.5-1; 5-10; 90-95 and 0.5-2%, respectively [4, 5]. Sufficient reserves of exchangeable magnesium in soils are the key to a good crop, because this form of element is available for absorption by plants. Significant spatial variation of magnesium content in soils and plants necessitates the development of mapping methods and search the informative indicators displayed on earth remote sensing data. One of the most famous indicators is the vegetation index (NDVI), its usage of which allows not only to mapping, but also to establish patterns of spatial variability of properties of soil and chemical composition of plants [6]. It is known that a higher value of NDVI in crops corresponds to a higher content of chlorophyll in plants [7, 8]. Studies have shown that NDVI is sensitive to changes in magnesium content in leaves of different plants [8]. Thus, it can be said that NDVI, chlorophyll and magnesium are interdependent characteristics of vegetation. The literature contains quite a lot of data of magnesium content in different soils, but there is insufficient information of the accordance of NDVI values to magnesium content in soils and plants. In addition, the spatial heterogeneity of magnesium content in soils with different SOM content and plants growing on them has not been sufficiently studied. Therefore, it is necessary to continue research in this direction.

The aim of this study were to: 1) perform forecast mapping of the content of magnesium in soils and plants with the use of NDVI calculated from Landsat 8 images (30-m resolution) as an indicator; 2) carry out a comparative assessment of high- and medium-SOM soils by the magnesium content in soils and plants growing on them; 3) estimate the correlations between magnesium content in soils, plants and NDVI values.

2 Objects and Methods

Field studies were performed on the Cis-Salair Plain in the south of Western Siberia (Novosibirsk oblast, Toguchin district, Ust'-Kamenka settlement). The investigated 2-km-long plot (100 ha) is found within the Irba and Khairuzovka river catchments. The following slope positions are distinguished within the plot: the first (upper) altitudinal step (280-310 m a.s.l.), the second altitudinal step (240-280 m a.s.l.) (Fig. 1). At the first altitudinal step (AS1) is distinguished by the predominant development of high-SOM soils with organic matter content (5-8%); medium-SOM soils predominate on the second altitudinal step (AS2) with organic matter content (3-5%) (Fig. 1).

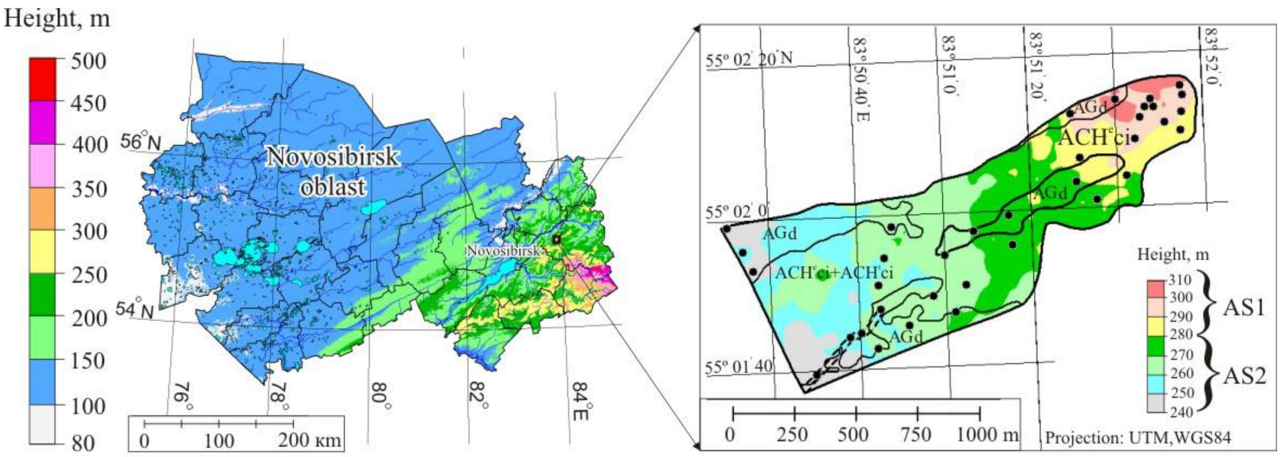

Figure 1. Study area and scheme of soil sampling. The investigation plot and the soil sampling scheme (solid lines – boundaries between soil polygons; dots – sampling points). Slope positions: AS1 – first altitudinal step, AS2 – second altitudinal step. Soils: ACH^{e}ci – eluviated clay-illuvial agrochernozems, ACH^{t}ci – dark-tonguing clay-illuvial agrochernozems, AGd – dark agrogray soils.

Soil samples (n=35) were taken from the plow layer (0-30 cm) following an irregular grid (Fig. 1). The coordinates of sampling points were determined with a Garmin eTrex Vista GPS.
The total magnesium (Mg_{tot}) content in soil was determined in powdered samples by the atomic emission analysis; exchangeable magnesium (Mg_{exch}) – by GOST 26487-85 (extraction with 1 M KCl) with termination on the atomic absorption spectrometer AAnalyst 400 (PerkinElmer Inc., USA.). The soil organic carbon (SOC) content was determined by the wet combustion method according by Tyurin, and then SOC was converted to SOM (Soil Organic Matter) by using a coefficient of 1.724 which estimates SOC 58% of the SOM total. The particle size distribution in the samples was determined by the Kachinskii procedure; pH of water suspension (1 : 2.5) with use potentiometer [9]. The total magnesium content in plant samples (Mg_{pl}) with the calculation on air dried mass was performed by the method of dry ashing with termination on the atomic absorption spectrometer AAnalyst 400 [2].The pool of aboveground phytomass of the oats-pea mixture was determined by the method of cutting plots (0.25 m^2 in size) in places of soil sampling with further drying and weighing of the cut phytomass. The predictive maps of soil and plant properties were developed using regression models. The NDVI of the oats-pea mixture was used as a predictor of

the properties of soils and plants. This index was calculated on the basis of Landsat 8 OLI image (July 14, 2013, 30-m resolution). The assessment of significance of the difference between mean values was performed using Student's t-test and the Mann-Whitney U test for Gaussian and non-Gaussian data, respectively.

3 Results and Discussion

Established relationships between NDVI and content of magnesium in soils and plants, and calculated regression equations (Fig. 2) allowed us to create the map of the yield for the entire investigated field (Fig. 3). NDVI explains 51% of variance of the content exchangeable magnesium in soils and 26% of variance of the content total magnesium in plants (Fig. 2). The positive correlation coefficient ($r = 0.71$) between NDVI and the content of exchangeable magnesium indicates its higher content in high-SOM soils on which the oat-pea mixture with large values of NDVI had grown (Fig. 2 A, 3 A, Table 1). The same dependence is noted for the total magnesium content in plants, where the correlation coefficient ($r=0.51$) between the studied parameters was positive (Fig. 2 B, 3 B, Table 1).

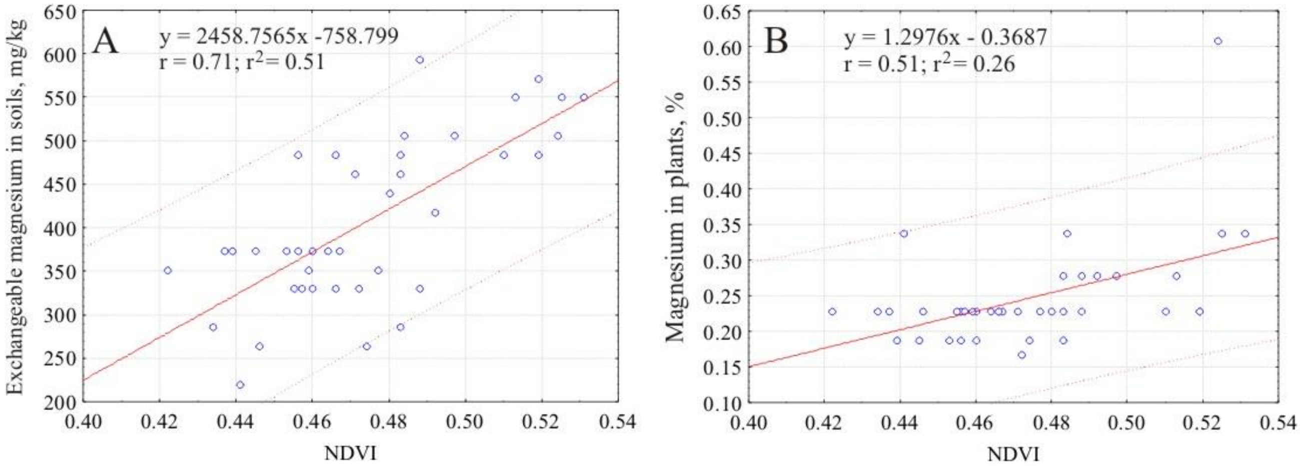

Figure 2. Regression models of the dependence between NDVI and magnesium content in soils (A) and plants (B).

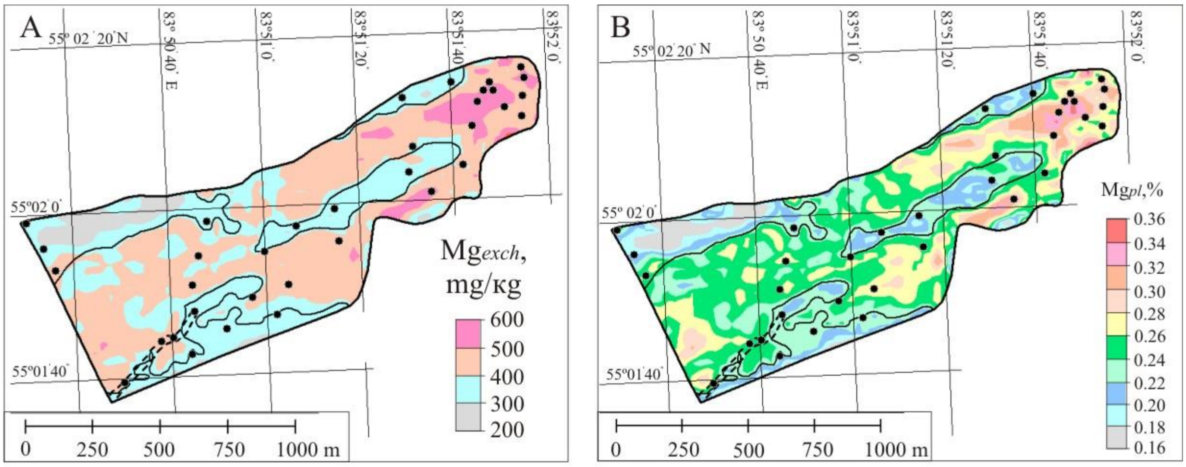

Figure 3. Forecast maps of the contents of exchangeable magnesium in soils (A), mg/kg; total magnesium in plants (B), %. Soil names are given in the caption to Fig. 1.

Various indices have been applied to assess the quality of the models (Table 2). According to F-criterion and it's probability (p), all the models and their determination coefficients are statistically significant (α = 0.05), as $F_{fact} > F_{table}$ (4.08). The statistical significance for regression coefficients (b) of all the models is confirmed by the values of t-criterion of regression coefficients above the critical value of 2.02. The free term of the equation in the model "*Total magnesium in plants*" is statistically insignificant, since the value of the student's t-test is less than the critical value, so it's was not taken into account when creating the map. The value of the RS criterion falls into the critical interval (3.83–5.35); hence, the residuals are characterized by a normal distribution. The MAPE value was in the range from 10 to 20%, which corresponds to a good accuracy of the prediction. Thus, on the basis of almost all statistical quality indicators, the model under consideration is in fairly good agreement with the actually measured data. It is incorrect to apply regression models obtained in this study for neighboring territories, other types of vegetation, and other dates of satellite images. These models are only valid for the investigated plot.

Table 1. Parameters of soils and vegetation

Параметры	Soils with SOM content		
	High-SOM soils	Medium-SOM soils	
	$ACH^e ci$ (n = 13)	$ACH^e ci + ACH^t ci$ (n = 7)	AGd (n = 15)
SOM, %	7.8 ± 1.2	5.0 ± 1.6*	4.5 ± 1.2*
pH of water suspension	5.85 ± 0.15	5.82 ± 0.11	5.68 ± 0.18
Clay, %	16.6; 15.4; 15.4	17.8; 13.5; 12.8	16.2 ± 3.3
Physical clay, %	50.1 ± 3.3	45.2 ± 2.7*	45.7 ± 3.4*
Mg_{tot}, mg/kg	7935 ± 1555	8897 ± 1173	8514 ± 1750
Mg_{exch}, mg/kg	504 ± 41	354 ± 45*	326 ± 71*
Proportion of Mg_{exch} in Mg_{tot}, %	6.6 ± 1.5	4.1 ± 0.9*	3.9 ± 1.1*
Mg_{pl}, %	0.29 ± 0.1	0.24 ± 0.03	0.22 ± 0.04**
Aboveground phytomass, g/m^2	130.5 ± 27.6	155.5 ± 40.3	142.8 ± 30.4
NDVI	0.503 ± 0.02	0.476 ± 0.01**	0.456 ± 0.01*

Above the line, the mean ± standard deviation is given for normally distributed data; for abnormally distributed data, the mean is given together with the median and mode (in parentheses). Under the line, the range (min–max) is indicated. * The indices that are statistically significantly (p < 0.01) different from the corresponding values in the high-SOM agrochernozems. ** The difference is significant at p<0.05. Soil names are given in the caption to Fig. 1.

Table 2. Quality indices of regression models

r, n=35	r^2	*F*-criterion, p<0.05	t-criterion for regression coefficient (b), p<0.05	t-criterion for the free term of the equation, p<0.05	RS	MAPE, %
Linear model "Exchangeable magnesium in soils», y=2458.7565x - 758.799						
0.71	0.51	37.76	6.15	3.99	4.4	15
Linear model " Total magnesium in plants», y=1.2976x - 0.3687						
0.51	0.26	12.38	3.51	1.51	4.2	13

RS-criterion is the test for normal distribution of the residuals, MAPE is the mean absolute percentage error, *y* is the dependent variable (predicted property of soils and plants), *x* is the independent variable (NDVI), n is the number of observations, and p is the probability of error.

On forecast maps (Fig. 3 A, B) showed the patterns of changes in content of magnesium in soils and plants down the slope. In medium-SOM soils (agro-chernozems, agro-dark gray) compared with high-SOM agro-chernozems, a lower content of exchangeable magnesium (in 1.5 times) was established, while the studied soils did not differ from each other in the content of total magnesium (Table 1). A greater content of exchangeable magnesium in high-SOM soils is associated with a higher content of physical clay (increases sorption capacity) and humus acids, which displace magnesium cations from the soil absorbing complex and increase the chemical weathering of primary minerals containing magnesium. This conclusion is confirmed by the positive correlation coefficients of the content of exchangeable magnesium with SOM and physical clay (Table 3).

It should be noted that according to the developed gradations [10], in high-SOM soils the content of exchangeable magnesium in soils was very high (>485 mg/kg), and in medium-SOM soils – increased (from 255 to 365 mg/kg). Magnesium content in plants corresponds to the optimal level [2]. However, the content of total magnesium in plants growing on high-SOM chernozems was in 1.2 times higher compared to the medium-SOM agro-gray soils (table. 2).

Thus, the application of NDVI as an indirect indicator of properties of the plow horizon of soils and plants and the models developed on its basis make it possible to save time, labor, and financial expenses on soil surveys and to improve informativeness of the maps.

Table 3. The Pearson and Spearman (marked by gray) correlation coefficients between the properties of the soils and vegetations characteristics (n=35)

Параметры	Mg_{tot}	Mg_{exch}	Mg_{pl}	SOM	pH	Physical clay	Clay	NDVI	Aboveground phytomass
Mg_{tot}	–								
Mg_{exch}	-0.38	–							
Mg_{pl}	x	0.32	–						
SOM	x	**0.86**	0.40	–					
pH	-0.35	0.45	x	x	–				
Physical clay	x	0.49	x	x	**0.54**	–			
Clay	x	x	x	-0.38	0.43	**0.78**	–		
NDVI	x	**0.71**	**0.51**	**0.72**	x	x	x	–	
Aboveground phytomass	x	x	x	x	x	x	x	x	–

Correlation coefficients of moderately strong and strong correlative relationships (p<0.01) are given in bold; coefficients attesting to moderate correlative relationships (p<0.01) are underlined; x – statistically insignificant correlative relationships (p>0.05).

3 Summary

1. In regression models, NDVI explained 51% of variance in the exchangeable magnesium content and 24% of variance in the content of total magnesium in plants. On the basis of the obtained regression models, forecast maps of the physical and chemical properties of soils on slopes have been developed. The assessment of the prediction accuracy shows that it is satisfactory for the exchangeable magnesium content (error 15%) and for the magnesium content in plants (13%).

2. The content of exchangeable magnesium in medium-SOM soils (agro-chernozems, agro-dark gray) averaged 340 mg/kg and was in 1.5 times lower compared to high-SOM agro-chernozems. The content of exchangeable magnesium in high- and medium-SOM soils was high and elevated, respectively. Differences by total magnesium content between soils with different SOM content were not revealed.

3. The content of total magnesium in the aboveground phytomass of the oat-pea mixture corresponds to the optimal level (0.22-0.29%). The content of total magnesium in plants growing on medium-SOM agro-dark gray soils was in 1.2 times lower than on high-SOM agro-chernozems.

4. The differences in the reserves of aboveground phytomass of oat-pea mixture on high- and medium-SOM soils are statistically insignificant. Correlations of aboveground phytomass reserves with the content of exchangeable magnesium in soils and NDVI values have not been established.

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