Application of digital terrain modelling to prediction of soil properties in the Prairie Ecozone

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ABSTRACT

We investigated possibilities and limitations of two approaches for a large-scaled analysis and prediction of spatial distribution of some soil properties in an agrolandscape in the Prairie Ecozone. The first approach is based on an implementation of nine types of digital terrain models and regression analysis. The second approach uses the concept of accumulation, transit, and dissipation zones. We found that topographic control of soil moisture and properties depending on soil moisture decreases with depth. The strongest dependence of soil properties on topography occurs within the depth of 0.3 m. For this soil layer, the dependence of soil properties on topography is supported by results of correlation and regression analyses. However, different correlation coefficients and regression equations describe a topographic control of a soil property in different seasons and years. This sets limits on the use of regression equations to predict spatial distribution of soil properties. At the same time, normalised minimum, maximum and mean values of soil properties in accumulation, transit and dissipation zones have little temporal dependence. This enables maps of accumulation, transit and dissipation zones to be used for prediction of distribution of actual minimum, maximum and mean values of soil properties in a landscape.

INTRODUCTION

Topography influences the migration and accumulation of substances moved by gravity along the land surface and in the soil, some climatic and meteorological characteristics, soil formation and vegetation cover properties (Moore et al., 1991; Shary et al., 1991; Florinsky, 1998). In recent years, powerful algorithms for digital terrain models (DTMs) derivation were proposed (e.g., Evans, 1980; Martz and De Jong, 1988; Quinn et al., 1991), a physical and mathematical theory of the topographic surface was developed (Shary, 1991, 1995), and digital elevation models (DEMs) – initial data for DTM derivation – have become widely available. Therefore, a trend of DTM application to solve a wide range of geoscientific problems is growing every year. Future development of digital terrain modelling is in a search and a selection of topographic measurands admitting of formalisation and modelling of landscape properties in quite pragmatic efforts.

Analysis and forecast of the spatial distribution and dynamics of soil properties are an important element of an adequate agriculture utilization of soils and a management of (agro)landscape sustainable development. Since topography is one of factors of the

pedogenesis, so quantitative information on landsurface is often used in soil studies (Aandahl, 1948; Troeh, 1964; Sinai et al., 1981; Burt and Butcher, 1985; Pennock et al., 1987; Stepanov, 1989; Carter and Ciolkosz, 1991; Odeh et al., 1991; Moore et al., 1993; Florinsky and Arlashina, 1998), modelling and prediction of soil properties (Moore et al., 1993; Boer et al., 1996; Cook et al., 1996; MacMillan et al., 1997). Generally, these predictions are based on regression equations describing dependencies of soil properties on topographic variables at each point of a landscape. However, the following points are less well-known: How much would relationships between soil and topographic attributes change with time (in different seasons and different years) and with depth? It is apparent that these dependencies are crucial factors for limitation, proficiency, and correctness of prediction methods. Besides, in some cases (e.g., prediction of spatial distribution of soil types, salinisation, and erosion instability) there are no reasons to define a value of a soil property in each point of a landscape. Knowledge on maximum, minimum and mean values on typical topographic features (i.e., on crests, slopes, and depressions) will suffice for this purpose. In this case, a problem of correct identification of these topographic features arises.

Peculiar features of the Prairie Ecozone in Manitoba are intensive agricultural use of almost all its territory. There were efforts to use DTMs in soil investigations of the Canadian Prairies in Saskatchewan and Alberta. Thus to analyse adequately soil properties, such as horizonation, Pennock et al. (1987) introduced a terrain segmentation according to signs and values of horizontal (k_h) and vertical (k_v) landsurface curvatures and slope gradient (G) (definitions and physical interpretations of these variables see in Florinsky (1998)). MacMillan et al. (1997) applied a similar technique to predict soil distribution within a landscape using data on G and relative relief (RF) as deciding factors. Pennock et al. (1987) and MacMillan et al. (1997), however, did not consider one very important topographic variable, namely specific catchment area (CA) (definition and physical interpretations see in Florinsky (1998)). It controls soil moisture distribution in a landscape as well as some other soil properties. One of the first methods for derivation of CA from DEMs was developed in Saskatchewan for studies of Canadian Prairie landscapes (Martz, de Jong, 1988).

Pennock et al. (1987) and MacMillan et al. (1997) also used more subjective criteria for terrain segmentation such as crests, slopes and depressions, as empirical threshold values of G and RF. This is because there are no rigorous quantitative definitions of qualitative geomorphic concepts of 'crest', 'slope', and 'depression'. An alternative is to use maps of accumulation, transit and dissipation zones (Shary et al., 1991) obtained with data on mean (H) and accumulation (K_a) landsurface curvatures (Shary, 1995). Using this approach, one can separate a landscape into partitions marked by accumulation, transit and dissipation of surface flows. Physical definitions of these terms are known (Shary, 1995). At the same time, these quantitative concepts have qualitative geomorphic analogies of depression, slope, and crest, respectively.

In this paper, we have investigated possibilities and limitations of two approaches for a large-scaled analysis and prediction of spatial distribution of selected soil properties in a low relief agrolandscape in the Prairie Ecozone. The first approach is based on an implementation of nine types of DTMs and regression analysis. The second approach uses the concept of accumulation,

transit, and dissipation zones. We investigated the temporal variab lity of topographic control on soil properties and variations in topographic influence on soil pro erties at increasing depth.
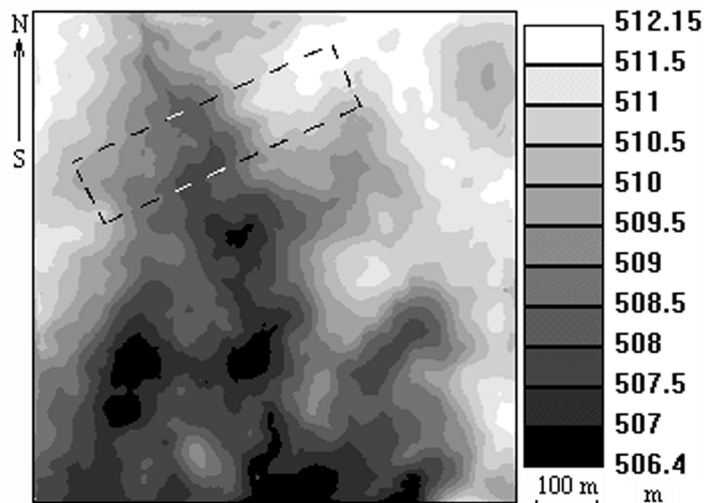
STUDY SITE

Fig. 1. The study site, the map of elevations. The plot is indicated by dashed lines.

This study builds on the work initiated in 1997 by Manning et al. (1998). The study site (Fig. 1) is located near the village of Miniota, Manitoba, Canada. This is the Miniota Precision Agriculture Research Site at Bell Farms. The site measures 809 by 820 m; the elevation difference is about 6 m. The agricultural land use is cereals and oilseeds. A detailed description of the area was completed by Fitzmaurice et al. (1999).

MATERIALS AND METHODS

A plot was selected within the study site (Fig. 1) for detailed investigation of the spatial variability of nitrogen response in a complex landscape (Manning et al., 1998). The plot includes a typical soil catena and measures about 450 by 150 m; differences in elevations are about 4.5 m. Ten adjacent 450 m equally spaced transects were allocated within the plot. Soil samples were collected in 210 points (21 points per each transect) at four depths – 0.3, 0.6, 0.9 and 1.2 m.

Contents of gravimetric soil moisture and residual sulphur, potassium, and phosphate were estimated in each point for all four depths. Also, thickness of the A and B horizons, the CO_3 and solum depths, as well as contents of the organic carbon and the total nitrogen in the A horizon were evaluated for each sample. Soil moisture at depths of 0.3 and 0.6 m was estimated for six seasons – May, June and August 1997 and 1998, and at depths of 0.9 and 1.2 m – in the same seasons except for August 1997. Sulphur, potassium and phosphate contents were evaluated in 2 seasons – in May 1997 and 1998. Thickness and depths of soil horizons as well as properties of the A horizon were measured in May 1997 Details of soil field and laboratory methods have been described by Manning et al. (1998).

An irregular DEM of the study site was obtained by GPS techniques. The DEM includes 4211 points. We converted the irregular DEM into regular one by the Delaunay triangulation and smooth interpolation (Watson, 1992). The grid interval of the regular DEM was 15 m. We calculated digital models of G, slope aspect (A), k_h, k_v, H and K by the method of Evans (1980). To calculate digital models of CA, topographic index (TI) and stream power index (SI) we applied the method of Martz and De Jong (1988). A map of accumulation, transit and dissipation zones (Fig. 2) was obtained by combination of data on H and K_a (Shary, 1995).
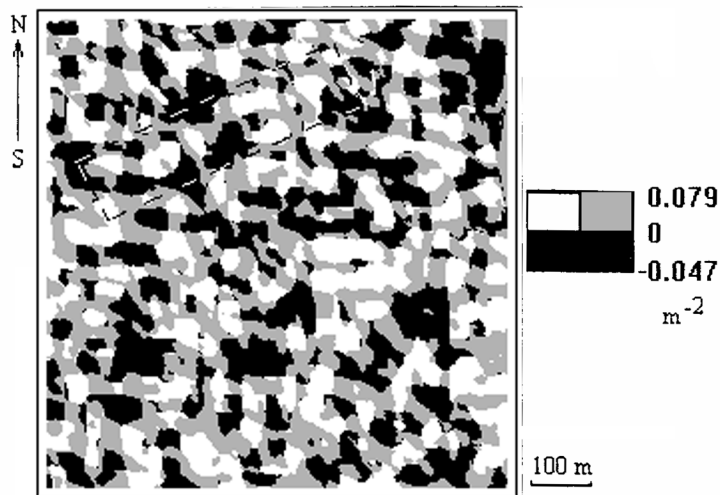
0.079
0
-0.047
m^{-2}

Fig. 2. The map of accumulation, transit and dissipation zones. The plot is indicated by dashed lines.

To estimate relationships between the soil properties and topographic attributes we performed linear multiple correlation analysis of all soil properties estimated with elevation (h), G, A, k_h, k, H, CA, TI and SI within the plot (Table 1). To describe these relationships the 'best' combination of the topographic variables marked by $R^2 \geq 0.25$ was chosen by the stepwise linear regression (Aivazyan et al., 1985). We used some regression equations (Table 2) for predictive mapping of spatial distribution of soil properties within the study site (Fig. 3).

Prediction of soil property distribution with the concept of accumulation, transit and dissipation zones included the following steps. First, we estimated minimum, maximum and mean values of soil properties under study (Table 3) for accumulation, transit and dissipation zones (Fig. 2). Second, we developed diagrams of the distribution of mean values of soil properties over these types of landforms (Fig. 4). Third, we performed a normalisation of values of the following soil properties marked by strong and temporally stable regular distribution over typical landforms: soil moisture at the depth of 0.3 m, potassium contents at the depths of 0.3 and 1.2 m, phosphate content at the depth of 0.3 m, the CO_3 and solum depths, the organic carbon and the total nitrogen contents. Normalisation is a common technique in data processing. The normalisation of values was done by a dividing the minimum, maximum and mean values of each property by the mean property value in dissipation zones. We selected mean property values in dissipation zones because they are, as a rule, minimum in the data set (Table 3). Consequently, we obtained normalised minimum, maximum and mean values of soil properties for three types of landforms (Table 3). An analysis of normalised values of soil properties obtained in different seasons and years demonstrated that these values are closely allied and are equal in some cases. This fact allowed us to compute time-average normalised minimum, maximum and mean values for soil moisture at the depth of 0.3 m, potassium contents at the depths of 0.3 and 1.2 m, and phosphate content at the depth of 0.3 m (Table 3). To evaluate absolute minimum, maximum and mean values of a soil property one has (a) to measure this property in some dissipation zones, (b) to calculate simple average of these measurements (it will be a mean value of the property in dissipation zones), and (c) to multiply this value by all other normalised minimum, maximum and mean values.

We applied the software LandLord (Florinsky et al., 1995) for the irregular DEM interpolation, topographic variables' calculation and mapping. Correlation and regression analyses were carried out by the software Statgraphics Plus 3.0.

Table 1. Point estimates of pairwise coefficients of linear correlation of soil properties with topographic variables (correlation coefficient and significance level of the correlation coefficient are presented for each pair of variables).

Soil property	Depth	Season	h	G	A	k_h	k_v	H	CA	TI	SI
Soil moisture	0.3 m	05/97	-0.45	-0.25	-0.03	-0.26	-0.46	-0.42	0.28	0.40	0.25
			(0.00)	(0.00)	(0.72)	(0.00)	(0.00)	(0.00)	0.00)	(0.00)	(0.00)
		07/97	-0.44	-0.31	-0.02	-0.33	-0.45	-0.46	0.36	0.52	0.33
			(0.00)	(0.00)	(0.81)	(0.00)	(0.00)	(0.00)	0.00)	(0.00)	(0.00)
		08/97	-0.34	-0.24	-0.05	-0.16	-0.35	-0.29	0.25	0.28	0.13
			(0.00)	(0.00)	(0.49)	(0.02)	(0.00)	(0.00)	0.00)	(0.00)	(0.07)
		05/98	-0.44	-0.21	-0.08	-0.33	-0.50	-0.48	0.31	0.48	0.39
			(0.00)	(0.00)	(0.26)	(0.00)	(0.00)	(0.00)	0.00)	(0.00)	(0.00)
		07/98	-0.33	-0.27	-0.25	-0.19	-0.25	-0.26	0.20	0.30	0.14
			(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	0.00)	(0.00)	(0.06)
		08/98	-0.40	-0.28	0.02	-0.24	-0.43	-0.39	0.26	0.38	0.21
			(0.00)	(0.00)	(0.77)	(0.00)	(0.00)	(0.00)	0.00)	(0.00)	(0.00)
	0.6 m	05/97	-0.26	-0.07	0.18	-0.08	-0.22	-0.17	0.08	0.12	0.06
			(0.00)	(0.30)	(0.01)	(0.27)	(0.00)	(0.02)	0.26)	(0.10)	(0.39)
		07/97	-0.28	-0.18	0.17	-0.14	-0.30	-0.25	0.20	0.22	0.10
			(0.00)	(0.01)	(0.02)	(0.05)	(0.00)	(0.00)	0.00)	(0.00)	(0.17)
		08/97	-0.20	-0.21	0.08	-0.18	-0.30	-0.28	0.28	0.27	0.14
			(0.00)	(0.00)	(0.25)	(0.01)	(0.00)	(0.00)	0.00)	(0.00)	(0.06)
		05/98	-0.44	-0.08	0.24	-0.24	-0.37	-0.35	0.32	0.36	0.32
			(0.00)	(0.28)	(0.00)	(0.00)	(0.00)	(0.00)	0.00)	(0.00)	(0.00)
		07/98	-0.26	-0.16	-0.17	-0.08	-0.16	-0.14	0.23	0.19	0.09
			(0.00)	(0.02)	(0.02)	(0.27)	(0.02)	(0.05)	0.00)	(0.01)	(0.19)
		08/98	-0.27	-0.09	0.14	-0.04	-0.19	-0.13	0.06	0.10	0.01
			(0.00)	(0.23)	(0.04)	(0.56)	(0.01)	(0.07)	0.37)	(0.17)	(0.85)
	0.9 m	05/97	-0.28	-0.09	0.16	-0.12	-0.24	-0.20	0.18	0.16	0.08
			(0.00)	(0.20)	(0.02)	(0.11)	(0.00)	(0.00)	0.01)	(0.02)	(0.24)
		07/97	-0.20	-0.02	0.12	0.01	-0.13	-0.06	0.17	0.09	0.09
			(0.00)	(0.78)	(0.11)	(0.86)	(0.06)	(0.37)	0.02)	(0.21)	(0.20)
		05/98	-0.34	0.01	0.26	-0.12	-0.27	-0.22	0.20	0.18	0.15
			(0.00)	(0.87)	(0.00)	(0.09)	(0.00)	(0.00)	0.00)	(0.01)	(0.03)
		07/98	-0.28	-0.16	-0.15	0.00	-0.03	-0.01	0.24	0.14	0.02
			(0.00)	(0.03)	(0.03)	(0.95)	(0.65)	(0.84)	0.00)	(0.05)	(0.75)
		08/98	-0.25	-0.08	0.08	-0.01	-0.18	-0.10	0.06	0.11	0.04
			(0.00)	(0.29)	(0.29)	(0.91)	(0.01)	(0.14)	0.41)	(0.12)	(0.59)
	1.2 m	05/97	-0.20	0.03	0.16	-0.01	-0.20	-0.12	0.17	0.10	0.09
			(0.00)	(0.65)	(0.02)	(0.88)	(0.00)	(0.10)	0.02)	(0.15)	(0.19)
		07/97	-0.33	-0.09	0.01	-0.06	-0.22	-0.16	0.24	0.22	0.13
			(0.00)	(0.20)	(0.91)	(0.43)	(0.00)	(0.03)	0.00)	(0.00)	(0.07)
		05/98	-0.26	-0.10	0.21	-0.15	-0.26	-0.23	0.19	0.21	0.13
			(0.00)	(0.15)	(0.00)	(0.04)	(0.00)	(0.00)	0.01)	(0.00)	(0.05)

		07/98	-0.39	-0.10	-0.12	-0.10	-0.16	-0.15	0.18	0.16	0.11
			(0.00)	(0.15)	(0.09)	(0.15)	(0.02)	(0.0?)	(0.01)	(0.03)	(0.12)
		08/98	-0.15	-0.08	0.10	0.01	-0.09	-0.04	0.15	0.15	0.08
			(0.04)	(0.29)	(0.16)	(0.90)	(0.20)	(0.5?)	(0.04)	(0.03)	(0.27)
Residual sulphur	0.3 m	05/97	-0.30	-0.08	-0.17	-0.07	-0.20	-0.15	-0.01	0.05	-0.01
			(0.00)	(0.26)	(0.02)	(0.34)	(0.00)	(0.0?)	(0.95)	(0.53)	(0.92)
		05/98	-0.17	-0.08	0.00	-0.08	-0.24	-0.13	0.00	0.08	0.04
			(0.01)	(0.29)	(0.98)	(0.25)	(0.00)	(0.0?)	(0.96)	(0.29)	(0.57)
	0.6 m	05/97	-0.22	0.05	0.11	0.10	-0.11	0.00	0.00	-0.09	-0.06
			(0.00)	(0.49)	(0.13)	(0.16)	(0.13)	(0.9?)	(0.98)	(0.20)	(0.37)
		05/98	-0.19	-0.09	0.00	0.08	-0.03	0.0?	-0.05	-0.07	-0.13
			(0.01)	(0.23)	(0.95)	(0.26)	(0.68)	(0.6?)	(0.51)	(0.33)	(0.06)
	0.9 m	05/97	-0.27	-0.02	-0.09	0.04	-0.06	0.0?	-0.06	-0.05	-0.05
			(0.00)	(0.73)	(0.23)	(0.57)	(0.43)	(0.9?)	(0.37)	(0.52)	(0.48)
		05/98	-0.28	-0.07	-0.08	0.10	-0.01	0.0?	-0.07	-0.08	-0.12
			(0.00)	(0.35)	(0.24)	(0.17)	(0.86)	(0.4?)	(0.32)	(0.28)	(0.08)
	1.2 m	05/97	-0.21	-0.04	-0.13	0.06	-0.04	0.0?	-0.06	-0.03	-0.04
			(0.00)	(0.62)	(0.07)	(0.42)	(0.55)	(0.8?)	(0.40)	(0.69)	(0.54)
		05/98	-0.23	-0.05	-0.08	0.07	-0.03	0.0?	-0.06	-0.03	-0.08
			(0.00)	(0.45)	(0.27)	(0.30)	(0.64)	(0.6?)	(0.42)	(0.65)	(0.29)
Residual potassium	0.3 m	05/97	-0.16	-0.23	-0.29	-0.05	-0.14	-0.11	0.12	0.16	0.03
			(0.02)	(0.00)	(0.00)	(0.51)	(0.05)	(0.1?)	(0.09)	(0.02)	(0.65)
		05/98	-0.17	-0.26	-0.20	-0.14	-0.15	-0.17	0.21	0.26	0.12
			(0.01)	(0.00)	(0.00)	(0.05)	(0.04)	(0.0?)	(0.00)	(0.00)	(0.08)
	0.6 m	05/97	-0.03	-0.21	-0.12	-0.06	-0.17	-0.13	0.05	0.13	0.01
			(0.63)	(0.00)	(0.08)	(0.37)	(0.02)	(0.0?)	(0.49)	(0.08)	(0.89)
		05/98	0.01	-0.27	0.00	-0.05	-0.11	-0.09	0.07	0.11	-0.08
			(0.90)	(0.00)	(0.97)	(0.46)	(0.13)	(0.2?)	(0.35)	(0.13)	(0.26)
	0.9 m	05/97	0.05	-0.25	-0.05	0.03	0.02	0.0?	-0.06	0.06	-0.11
			(0.48)	(0.00)	(0.48)	(0.64)	(0.76)	(0.6?)	(0.34)	(0.42)	(0.14)
		05/98	0.14	-0.32	0.02	0.07	0.05	0.0?	-0.08	0.00	-0.24
			(0.06)	(0.00)	(0.96)	(0.31)	(0.46)	(0.3?)	(0.26)	(0.95)	(0.00)
	1.2 m	05/97	0.24	-0.19	-0.09	0.16	0.22	0.2?	-0.21	-0.13	-0.28
			(0.00)	(0.00)	(0.23)	(0.03)	(0.00)	(0.0?)	(0.00)	(0.06)	(0.00)
		05/98	0.22	-0.30	-0.05	0.06	0.16	0.1?	-0.17	-0.07	-0.30
			(0.00)	(0.00)	(0.45)	(0.42)	(0.02)	(0.0?)	(0.02)	(0.36)	(0.00)
Residual phosphate	0.3 m	05/97	-0.25	-0.15	-0.05	-0.18	-0.33	-0.30	0.23	0.31	0.23
			(0.00)	(0.04)	(0.50)	(0.01)	(0.00)	(0.0?)	(0.00)	(0.00)	(0.00)
		05/98	-0.28	-0.25	0.00	-0.25	-0.35	-0.35	0.42	0.44	0.27
			(0.00)	(0.00)	(0.95)	(0.00)	(0.00)	(0.0?)	(0.00)	(0.00)	(0.00)
	0.6 m	05/97	-0.33	-0.23	0.04	-0.17	-0.36	-0.31	0.37	0.42	0.27
			(0.00)	(0.00)	(0.55)	(0.01)	(0.00)	(0.0?)	(0.00)	(0.00)	(0.00)
		05/98	-0.21	-0.26	0.05	-0.09	-0.25	-0.20	0.27	0.33	0.15
			(0.00)	(0.00)	(0.45)	(0.20)	(0.00)	(0.0?)	(0.00)	(0.00)	(0.04)

0.9 m	05/97	-0.14	-0.14	0.07	-0.15	-0.25	-0.23	0.12	0.21	0.13
		(0.06)	(0.04)	(0.31)	(0.04)	(0.00)	(0.00)	(0.08)	(0.00)	(0.07)
	05/98	-0.08	-0.24	0.01	-0.13	-0.25	-0.22	0.22	0.23	0.04
		(0.28)	(0.00)	(0.95)	(0.08)	(0.00)	(0.00)	(0.00)	(0.00)	(0.62)
1.2 m	05/97	0.03	-0.12	0.06	-0.08	-0.14	-0.13	0.13	0.11	0.02
		(0.72)	(0.08)	(0.39)	(0.27)	(0.05)	(0.08)	(0.07)	(0.13)	(0.74)
	05/98	0.00	-0.23	-0.04	-0.09	-0.10	-0.11	0.15	0.18	0.01
		(0.98)	(0.00)	(0.53)	(0.19)	(0.16)	(0.11)	(0.04)	(0.01)	(0.90)
Thickness of the A horizon	05/97	-0.23	-0.02	0.03	-0.05	-0.24	-0.17	0.18	0.15	0.12
		(0.00)	(0.74)	(0.69)	(0.46)	(0.00)	(0.02)	(0.01)	(0.04)	(0.08)
Thickness of the B horizon	05/97	0.01	-0.09	-0.08	-0.02	0.13	0.06	-0.11	-0.07	-0.14
		(0.94)	(0.44)	(0.46)	(0.88)	(0.25)	(0.60)	(0.30)	(0.54)	(0.19)
CO_3 depth	05/97	-0.16	-0.20	0.05	-0.24	-0.41	-0.37	0.24	0.34	0.24
		(0.02)	(0.01)	(0.53)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Solum depth	05/97	-0.22	-0.20	0.04	-0.25	-0.39	-0.37	0.27	0.37	0.26
		(0.00)	(0.00)	(0.59)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Organic carbon in the A horizon	05/97	-0.41	-0.27	-0.34	-0.32	-0.40	-0.43	0.23	0.45	0.29
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Total nitrogen in the A horizon	05/97	-0.30	-0.37	-0.32	-0.21	-0.29	-0.30	0.19	0.38	0.14
		(0.00)	(0.00)	(0.00)	(0.02)	(0.00)	(0.00)	(0.04)	(0.00)	(0.13)

Table 2. Regression equations describing dependencies of some soil properties on topographic variables.

| Dependent variable	Equation	R^2
Soil moisture, 0.3 m, 05/97	$573.8 - 1.08h - 2.48G + 0.01A - 17.3k_v + 0.25SI$	0.36
Soil moisture, 0.3 m, 07/97	$380.26 - 0.72h - 1.44G + 0.01A + 17312.4k + 17300.7k_v - 34623.7H + 0.49TI$	0.42
Soil moisture, 0.3 m, 05/98	$408.11 - 0.76h - 3.56G + 0.01A - 16.91k_v - 0.49TI + 1.16SI$	0.43
Soil moisture, 0.3 m, 08/98	$446.14 - 0.83h - 2.11G + 0.01A - 13.85k_v$	0.34
Soil moisture, 0.6 m, 05/97	$644.21 - 1.24h - 2.08G + 0.02A + 16913.4k_i + 16904.7k_v - 33822.1H + 0.61SI$	0.38
Residual phosphate, 0.6 m, 05/97	$196.15 - 0.38h - 1.84G + 0.01A + 17.99k_h - 22.62H + 0.0004CA + 0.42SI$	0.29
Residual phosphate, 0.3 m, 05/98	$381.52 - 0.72h - 3.77G + 0.01A - 38.4k_v + 0.003CA$	0.28
The CO_3 horizon depth	$-1006.08 + 2.02h - 13.17G + 0.04A - 188.8k_v + 66.13H + 3.93SI$	0.25
Organic carbon content in the A horizon	$53.75 - 0.1h - 0.35G - 0.001A - 2.55k_v + 0.1SI$	0.39
Total nitrogen content in the A horizon	$6.75 - 0.01h - 0.1G - 0.19k_v - 0.02TI + 0.03TI$	0.33
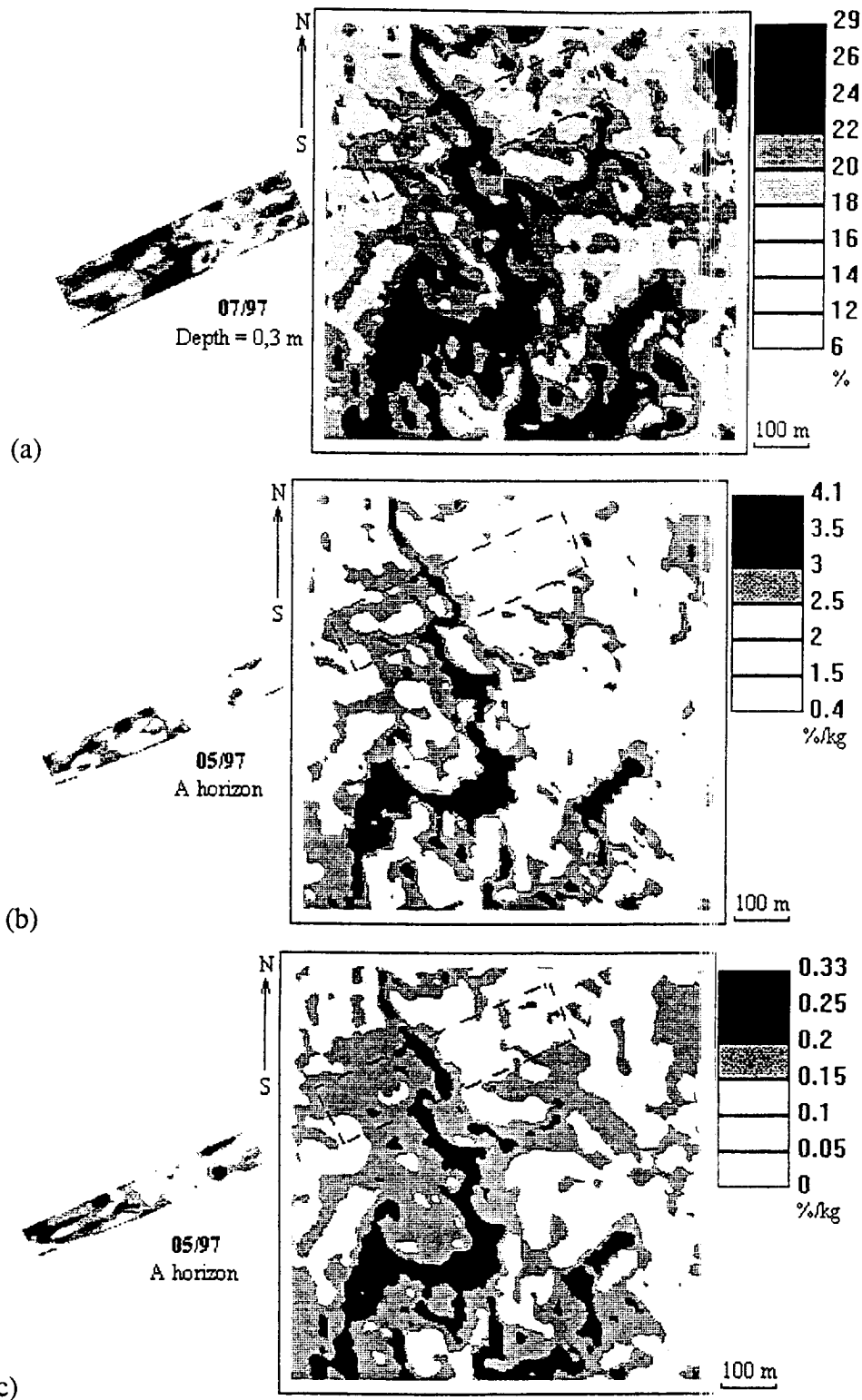
Fig. 3. Maps of actual distribution of soil properties within the plot and prediction maps of the same properties for the study site obtained with regression equations: (a) the gravimetric soil moisture content in the depth of 0.3 m, June 1997, (b) the organic carbon content in the A horizon, (c) the total nitrogen content in the A horizon.

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Table 3. Minimum, maximum and mean values of soil properties over dissipation, transit and accumulation zones, actual and normalised values are in numerator and denominator, relatively.

Soil property	Dissipation zone			Transit zone			Accumulation zone		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Soil moisture, 0.3 m, 05/97	12.46	29.91	20.75	13.1	30.62	21.46	15.78	34.09	24.83
	0.60	1.44	1	0.63	1.48	1.03	0.76	1.64	1.20
Soil moisture, 0.3 m, 05/98	11.3	25.8	18.69	10.78	24.87	19.72	11.14	34.05	22.56
	0.60	1.38	1	0.58	1.33	1.06	0.60	1.82	1.21
Soil moisture, 0.3 m, 07/97	13.43	23.35	18.78	13.89	26.59	19.81	11.87	29.71	21.84
	0.72	1.24	1	0.74	1.42	1.05	0.63	1.58	1.16
Soil moisture, 0.3 m, 07/98	17.95	35.05	25.52	19.08	35.53	26.64	19.09	37.11	27.83
	0.70	1.37	1	0.75	1.39	1.04	0.75	1.45	1.09
Soil moisture, 0.3 m, 08/97	9.26	21.68	15.01	7.18	21.51	15.07	9.42	24.39	16.72
	0.62	1.44	1	0.48	1.43	1	0.63	1.62	1.11
Soil moisture, 0.3 m, 08/98	13.12	23.77	19.21	12.65	26.02	20.3	13.89	30.71	21.88
	0.68	1.24	1	0.66	1.35	1.06	0.72	1.60	1.14
Average soil moisture, 0.3 m	0.65	1.35	1	0.64	1.40	1.04	0.68	1.62	1.16
Potassium, 0.3 m, 05/97	115	1160	239.02	123	437	216.68	96	533	254.83
	0.48	4.85	1	0.51	1.83	0.91	0.40	2.23	1.07
Potassium, 0.3 m, 05/98	70	841	221.67	123	391	211.32	106	531	248.94
	0.32	3.79	1	0.55	1.76	0.95	0.48	2.40	1.12
Average potassium, 0.3m	0.40	4.32	1	0.53	1.80	0.93	0.44	2.32	1.10
Potassium, 1.2 m, 05/97	95	222	147.42	82	244	135.21	10	252	122.81
	0.64	1.51	1	0.56	1.66	0.92	0.07	1.71	0.83
Potassium, 1.2 m, 05/98	90	247	164.06	99	292	159.35	58	299	140.04
	0.55	1.51	1	0.60	1.78	0.97	0.35	1.82	0.85
Average potassium, 1.2 m	0.60	1.51	1	0.58	1.72	0.95	0.21	1.77	0.84
Phosphate, 0.3 m, 05/97	2	32	11.42	3	41	14.6	4	46	17.33
	0.18	2.80	1	0.26	3.59	1.28	0.35	4.03	1.52
Phosphate, 0.3 m, 05/98	4	49	12.53	3	40	15	4	52	20.16
	0.32	3.91	1	0.24	3.19	1.20	0.32	4.15	1.61
Average phosphate, 0.3 m	0.25	3.36	1	0.25	3.39	1.24	0.34	4.09	1.57
CO_3 depth	0	54	24.94	0	112	37.03	0	140	43.49
	0	2.17	1	0	4.49	1.48	0	5.61	1.74
Solum depth	9	54	28.58	14	99	37.69	9	140	44.29
	0.31	1.89	1	0.49	3.46	1.32	0.31	4.90	1.55
Organic carbon	1.1	2.63	1.98	1.04	3.85	2.28	0	0.28	0.14
	0.56	1.33	1	0.53	1.94	1.15	0.95	2.05	1.35
Total nitrogen	0	0.24	0.12	1.89	4.05	2.68	0.04	0.33	0.17
	0	2	1	0	2.33	1.17	0.33	2.75	1.42

RESULTS AND DISCUSSION

Results of correlation analysis (Table 1) demonstrate that soil moisture at the depth of 0.3 m depends essentially on all topographic variables except A. However, different correlation coefficients were obtained for different seasons and years. As this takes place, there is a retention of lower correlations with G, k_h, CA, and SI, and higher correlations with TI, k_v and H. The latter conforms to physical interpretation of these topographic variables as found in previous investigations (Florinsky, 1998) and results of other authors (Sinai et al., 1981; Burt and Butcher, 1985). Soil moisture has higher correlation with k_v rather than with k_h, so within the study site the main mechanism of flow accumulation is relative deceleration; flow convergence is the secondary factor. Soil moisture has higher correlations with TI rather than with CA and G because TI includes data on CA and G (Florinsky, 1998). Absolute values of correlation coefficients decrease and at times become non-significant with increasing the depth. This demonstrates the decrease of topographic control of soil moisture with the depth.

Correlation analysis (Table 1) also demonstrated that the spatial distribution of residual sulphur content is not generally controlled by topographic variables: correlation coefficients are low and not significant, except h. This result was not expected because it is in contradiction with evidences of sulphur redistribution by water flows according to the relief (Kovda, 1973). It is possible that this is due to the gypsum existing copiously in this landscape.
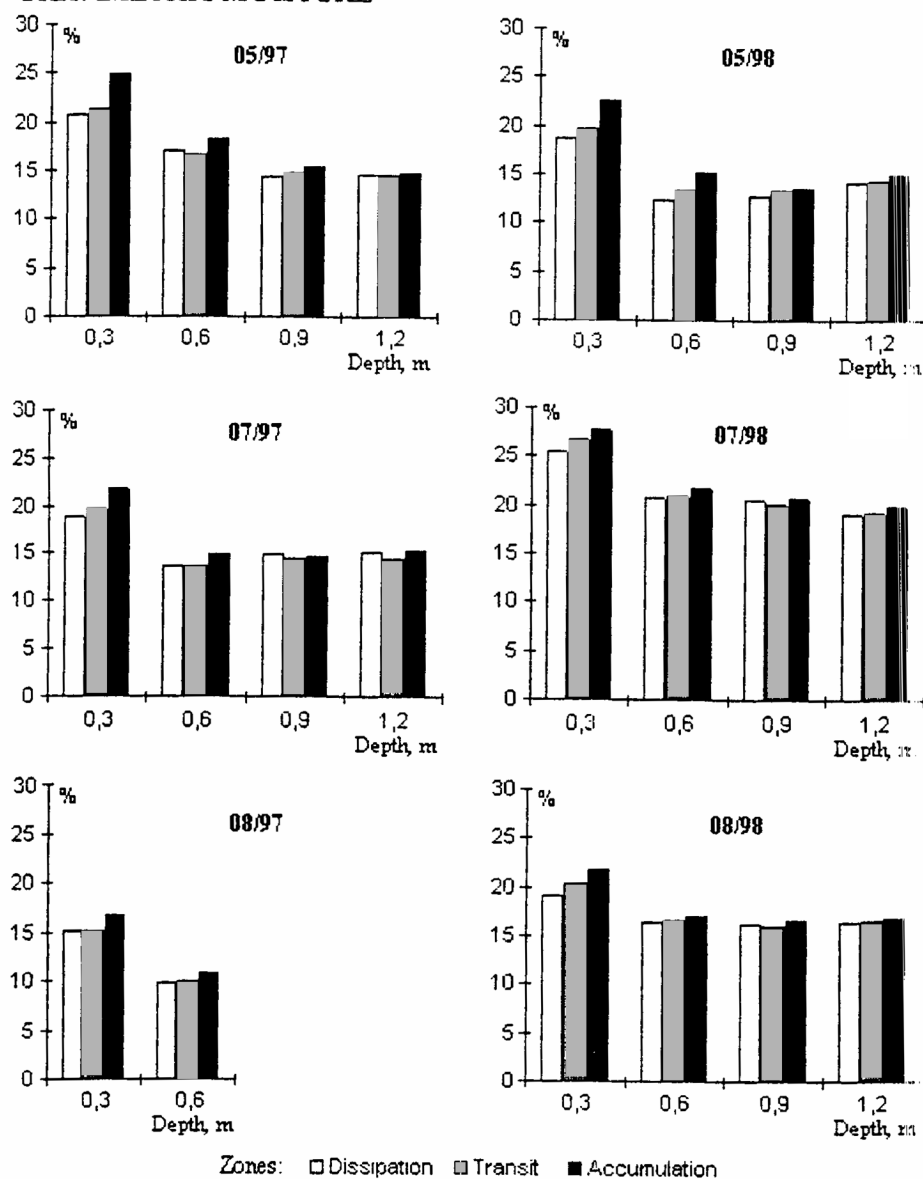
Results of correlation analysis (Table 1) shows only a weak dependence of that the spatial distribution of residual potassium content on topographic variables; G plays the most important role. Correlations slightly increase with the depth. At the same time, for the depths of 0.3 and 0.6 m correlation coefficients (Table 1) favour the view that topography influences the spatial distribution of residual phosphate content through the control of the soil moisture regime (Kovda, 1973; Moore et al., 1993). Absolute values of correlation coefficients decrease with increasing the depth. This demonstrates the decrease of topographic control of phosphate content with the depth. Relationships of potassium and phosphate contents with the topography are described by different correlation coefficients in different years (Table 1).

Correlations of thickness of the A and B horizons with topographic variables are low or not significant (Table 1). This is in contradiction with well-known topographic control of thickness of soil horizons (Aandahl, 1948; Pennock et al., 1987; Carter and Ciolkosz, 1991; Moore et al., 1993). At the same time, we found relatively high correlation coefficients for the CO_3 and solum depths with topographic attributes, specifically with k_v, H, and TI (Table 1). The same trend can be seen for the contents of the organic carbon and the total nitrogen in the A horizon (Table 1). These are due to the fact that the CO_3 and solum depths as well as the organic carbon and the total nitrogen contents depend on soil moisture regime which in turn depends on relief (Aandahl, 1948; Kovda, 1973; Moore et al., 1993; Florinsky and Arlashina, 1998).

As a result of the regression analysis (Table 2) we obtained four equations for soil moisture measured at the depth of 0.3 m and one equation for the depth of 0.6 m. The equations obtained for different seasons and years have different sets of independent variables and different coefficients. h, G, A and k_v were inserted into all these equations as independent

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variables. This is a single common feature of these equations. R^2 are not higher than 0.43, so up to 43% of soil moisture variability at the depth of 0.3 m can be explained by topographic attributes. We suppose that generally this is a good result because we took into consideration only topographic influence on moisture distribution in the landscape. Other important factors, such as, mechanical content of the soil, were not included in regression analysis.
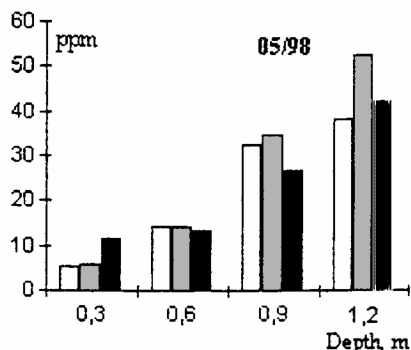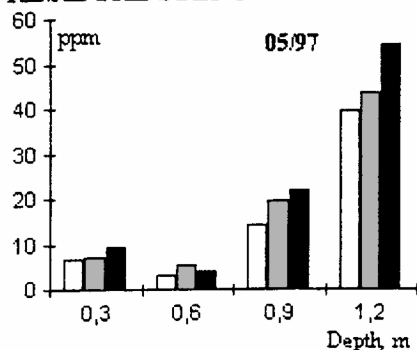
GRAVIMETRIC MOISTURE

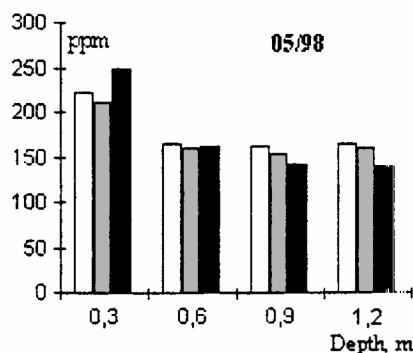Zones: □ Dissipation ▨ Transit ■ Accumulation

(a)

Also, we obtained regression equations (Table 2) explaining 28–29% of the variability of the phosphate spatial distribution at the depths of 0.3 and 0.6 m, 25% of the variability of CO_3 horizon depth, 39% and 33% of the variability of the organic carbon and the total nitrogen contents, respectively.

Comparable analysis of maps of actual soil properties within the plot and predictive maps of the study site (Fig. 3) shows that predictive mapping with results of regression analysis may render general features of spatial distribution of soil properties. However, the fact that for different seasons and years one can obtain different regression equations calls into question possibility of wide applications of this approach.

Fig. 4. Diagrams of the distribution of actual mean values of soil properties over accumulation, transit and dissipation zones: (a) the gravimetric soil moisture content, (b) contents of residual sulphur, potassium and phosphate, (c) thickness of the A and B horizons, the CO and solum depths, and contents of the organic carbon and the total nitrogen in the A horizon.
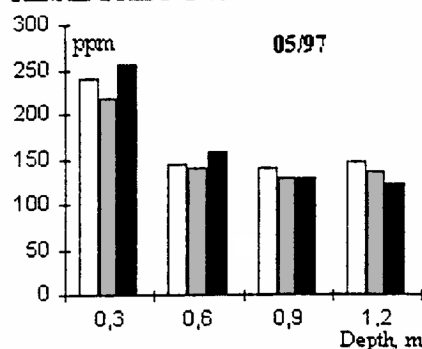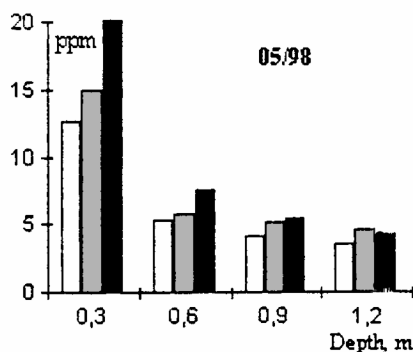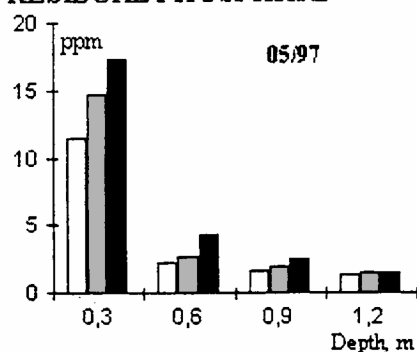
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RESIDUAL SULFUR

RESIDUAL POTASSIUM

RESIDUAL PHOSPHATE

Zones: □ Dissipation ▨ Transit ■ Accumulation

(b)

An analysis of soil moisture distribution over accumulation, transit and dissipation zones (Fig. 4a) demonstrates a strong and obvious trend for the depth of 0.3 m: accumulation zones (depressions), dissipation zones (crests), and transit zones (slopes) are marked by maximum, minimum and medium soil moisture contents, correspondingly. This trend becomes less well defined and disappears with the depth. We have to stress that this is obvious trend; a novelty is a correct recognition of depressions, slopes, and crests (see Introduction). It is important that at the depth of 0.3 m normalised minimum, maximum and mean values of the soil moisture content over different landforms are characterised by low temporal variability, as distinct from correspondent absolute minimum, maximum and mean values (Table 3). Therefore, we suppose that soil moisture prediction with the maps of accumulation, transit, and dissipation zones is more appropriate than with regression equations.

For the depths of 0.9 and 1.2 m an analysis of the sulphur distribution over accumulation, transit and dissipation zones (Fig. 4b) demonstrates a trend akin to the moisture distribution: maximum content is in depressions, minimum content is on crests, medium content is on slopes. However, this trend is not temporally stable: it cannot be seen for May 1998. The diagrams of the potassium distribution over typical landforms (Fig. 4b) demonstrate a temporally stable trend of its distribution for the depths of 0.3 and 1.2 m. For the depth of 0.3 m one can see minimum potassium contents in transit zones and maximum contents in

accumulation zones. This could have resulted from redistribution down slope of potassium from slope soils and its accumulation in depression soils. For the depth of 1.2 m one can see minimum potassium content in accumulation zones and maximum content in dissipation zones. The diagrams of phosphate distribution over typical landforms (Fig 4b) show as expected, a strong and temporally stable trend of its distribution for the depth of 0.3 m (and slight trend for the depths of 0.6 and 0.9 m). These trends are the same as the moisture trend: maximum content is in depressions, minimum content is on crests, and medium content is on slopes. The most part of normalised minimum, maximum and mean values of potassium and phosphate contents over different landforms are marked by low temporal variability (Table 3). This allows one to apply maps of accumulation, transit, and dissipation zones to predict distribution of residual potassium and phosphate contents in landscapes.

We found a low trend of the distribution of the A horizon thickness over accumulation, transit, and dissipation zones (Fig. 4c): maximum thickness is in depressions, minimum thickness is on crests, and medium thickness is on slopes. There are not the same trends for the B horizon thickness (Fig. 4c). At the same time, data on the CO_3 and solum depths (Fig. 4c and Table 3) demonstrate an expected strong trend: maximum depth is in depressions, minimum depth is on crests, and medium depth is on slopes. The same trend can be seen for the contents of the organic carbon and the total nitrogen in the A horizon (Fig. 4c and Table 3). This also allows one to apply maps of accumulation, transit, and dissipation zones to predict distributions of these soil properties in landscapes.

Different natural conditions can be marked by different normalised minimum, maximum and mean values of soil properties. In addition, they can be scale-depended values.

(c)
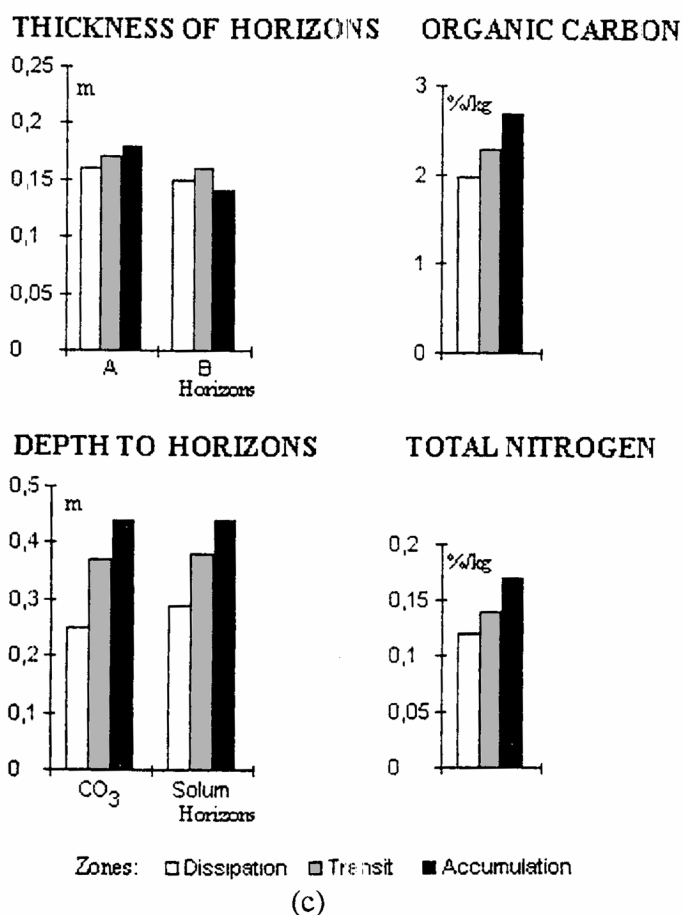
CONCLUSIONS

1. Results of the detailed research transect studies were used with digital terrain modeling techniques and extrapolated to the broader field scale which is the more traditional practical farm management unit in complex undulating glacial till landscapes.

2. Topographic control of soil moisture and properties depending on soil moisture decreases with depth. The strongest dependence of soil properties on topography occurs within the depth of 0.3 m.

3. For the upper soil layer the dependence of soil properties on topography is obvious and is supported by results of correlation and regression analyses. However, different correlation coefficients and regression equations describe a topographic control of a soil property in different seasons and years. This sets limits on the use of regression equations to predict spatial distribution of soil properties.

4. Normalised minimum, maximum and mean values of soil properties in accumulation, transit and dissipation zones have little temporal dependence. This enables maps of accumulation, transit and dissipation zones to be used for prediction of distribution of actual minimum, maximum and mean values of soil properties in a landscape.

5. Reproducibility, simplicity, and flexibility of DTM techniques characterise their practical potential in soil science and agriculture.

ACKNOWLEDGEMENTS

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