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Quantitative topographic analysis of gilgai soil morphology

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Abstract

For a gilgai soil complex we estimated the effect of overland and intrasoil substance flows on Vertisol development using concepts of topographic control of lateral substance movement by gravity rather than direct observations and measurements of these processes. First, we studied relationships between gilgai microtopographic characteristics and some Vertisol morphological properties, namely, depth to parent material (C) and calcium carbonate-enriched (B_{Ca}) horizons. Secondly, we checked if microtopographic characteristics of the C horizon surface influence some Vertisol properties by examining the B_{Ca} horizon depth. We used digital models of quantitative topographic variables. We concluded that the dominant mechanism controlling the C horizon depth is pedoturbation. Also, pedoturbation can be important in the development of the B_{Ca} horizons. However, variations in the C and the B_{Ca} horizon depths are not dictated by pedoturbation only. Our analysis showed that key factors influencing the C and the B_{Ca} horizon depths are overland and intrasoil lateral migration and accumulation of water, solution and solid substances. The C horizon depth depends on the landsurface topographic characteristics, namely: horizontal, vertical and mean curvatures, specific catchment area, topographic and stream power indices. The B_{Ca} horizon depth is significantly affected by the same set of topographic attributes of both the landsurface and the C horizon surface. The B_{Ca} and the C horizon depths, as a rule, depend more on specific catchment area, topographic and stream power indices than on horizontal, vertical and mean curvatures of the landsurface and the C horizon surface. This is because specific catchment area, topographic and stream power indices take into account a relative location of a point in a microcatena. Utilization of quantitative topographic variables allows us to explain 82% of

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variation in the B_{Ca} horizon depth and to suggest that topography is the main factor in the B_{Ca} horizon formation.

Keywords: Vertisols; gilgai; topography; digital elevation models; quantitative analysis

1. Introduction

Vertisols cover about 3,200,000 km^2 and are developed under a range of climatic and geomorphic conditions. Vertisol parent materials include basaltic intrusions, calcareous rocks, gneisses, marine alluvial materials. Generally, they have a natural plant cover of grasses and slow-growing deep-rooting tree species. The distinguishing properties of the Vertisol are high clay content (at least 30%), low organic matter content (between 0.5 and 3%), and marked changes in volume with cyclical variation of the moisture regime resulting in hardness when dry and plasticity when wet as well as seasonal crack and slickenside formation (Dudal, 1963; Buol et al., 1973; Ahmad, 1983; Dudal and Eswaran, 1988).

A landsurface microrelief named *gilgai* is typical for nearly half of Vertisol areas (Buol et al., 1973). Gilgai consist of alternating microdepressions and micromounds. An altitude difference between a microdepression and a micromound is, as a rule, in the range from 0.02 to 1 m. The distance between micromounds is in the range of 0.3 to 60 m (Hallsworth et al., 1955; Edelman and Brinkman, 1962; Paton, 1974). Several theories of gilgai formation have been proposed (Hallsworth et al., 1955; Edelman and Brinkman, 1962; Buol et al., 1973; Paton, 1974; Wilding and Tessier, 1988; Kovda et al., 1992). Beckmann et al. (1984) noted that these theories are generally based on phenomena of soil swelling and shrinking. The most popular model of the gilgai development is based on pedoturbation (Hallsworth et al., 1955; Buol et al., 1973; Ahmad, 1983). According to this model, when a wet clay soil dries, large cracks develop and are infilled with surficial and sidewall soil material caused by erosion and bioturbation. Following re-wetting, swelling of the infilled and adjacent soil mass leads to oblique and upward movement of the soil material resulting in gilgai formation (Wilding and Tessier, 1988).

However, Vertisol properties do not depend solely on pedoturbation (Buol et al., 1973; Kovda et al., 1992). One of the most important factors of soil formation is relief (Huggett, 1975; Gerrard, 1981). Thus once a gilgai has been formed, its microtopographic characteristics can influence further Vertisol development. Indeed, Templin et al. (1956) found that the A_1 horizon thickness and colour vary with position in a gilgai. The reason is that soil material enriched with organic matter is washed off micromounds into microdepressions (Buol et al., 1973). Kovda et al. (1992) argued that the recent development of the soil below a gilgai microcatena is principally controlled by water distribution and redistribution depending on microrelief characteristics. Thus, gilgai microtopography influences the spatial distribution of soil moisture, pH, salt and free iron content (Kovda et al., 1992).

The studies of Templin et al. (1956) and Kovda et al. (1992) used qualitative description of topographic characteristics. Kovda et al. (1992) used a set of soil data collected in only three points of a gilgai microcatena, namely, in a microdepression, a microslope and a micromound. Indeed, it maybe a methodological flaw to investigate the influence of microtopography (which is a *spatially distributed* phenomenon) on properties of soil (which is also a *spatially distributed* phenomenon) using data collected *at only three points* of a microcatena. It is better to study the influence of topography on soil properties described quantitatively. In that case we have to use *quantitative* descriptions of topographic properties too. Thus, to obtain impartial results and to develop a quantitative model of the gilgai influence on Vertisol properties, it is reasonable to employ (a) spatially distributed soil and topographic data, and (b) a quantitative description of topography.

The following quantitative topographic variables are most often used in landscape and, specifically in soil, studies (Moore et al., 1991; Shary et al., 1991; Florinsky, 1995): elevation (h), gradient (G), aspect (ASP), horizontal (k_h), vertical (k_v) and mean (H) landsurface curvatures, specific catchment area (CA), topographic (TI) and stream power (SI) indices (Table 1). Topographic variables are connected with several processes effecting soil development, among them hydrological processes. G controls flow velocity, runoff and soil loss (Wischmeier and Smith, 1978); ASP influences flow direction, insolation, intensity of rain evaporation, snow detention and melting (Zakharov, 1940; Young, 1972); h determines vertical soil zonality in mountainous region; G, ASP and h in many respects affect microclimate (Geiger, 1966); k_h controls flow convergence – flows diverge when $k_h > 0$ while flows converge when $k_h < 0$ (Kirkby and Chorley, 1967); k_v determines relative deceleration of flow movement – flows accelerate when $k_v > 0$ while flows decelerate when $k_v < 0$ (Shary, 1991); H combines information on both flow convergence and relative deceleration of flows (Shary, 1995); CA is the measure of a catchment area (Speight, 1968); TI is the theoretical estimation of water flow accumulation (Beven and Kirkby, 1979; Quinn et al., 1991); SI is the measure of the potential erosive power of overland water flows (Moore et al., 1991).

G, ASP, k_h, k_v, H, CA, TI and SI influence the following soil properties: moisture (Zakharov, 1940; Troeh, 1964; Anderson and Burt, 1978; Beven and Kirkby, 1979; O'Loughlin, 1981; Sinai et al., 1981; Burt and Butcher, 1985; Quinn et al., 1991; Kuryakova et al., 1992), thickness of soil horizons (Norton and Smith, 1930; Aandahl, 1948; Acton, 1965; Walker et al., 1968; Kachanoski et al., 1985a; Pennock et al., 1987; Carter and Ciolkosz, 1991; Moore et al., 1993; Bell et al., 1994; Gessler et al., 1995), granulometric composition (Odeh et al., 1991; King et al., 1994), density (Kachanoski et al., 1985a,b), pH, organic

Table 1
Definitions and formulae of some topographic variables (Florinsky and Kuryakova, 1996)

Topographic variable, unit	Definition and formula
Elevation, m	Elevation above sea level in a given point of the landsurface.
Gradient, degree	An angle between a tangent and horizontal planes in a given point of the landsurface, $G = \arctan\sqrt{p^2+q^2}$ [a](Shary, 1991).
Aspect, degree	An angle clockwise from north to a projection of an external normal vector to a horizontal plane in a given point of the landsurface, $\mathrm{ASP} = \arctan(\frac{q}{p})$ [a](Shary, 1991).
Vertical curvature, m^{-1}	A curvature of a normal section of the landsurface by a plane including a gravity acceleration vector in a given point of the landsurface, $k_v = -\frac{p^2r+2pqs+q^2t}{(p^2+q^2)\sqrt{(1+p^2+q^2)^3}}$ [a](Shary, 1991).
Horizontal curvature, m^{-1}	A curvature of a normal section of the landsurface. This section is orthogonal to the section with k_v in a given point of the landsurface, $k_h = -\frac{q^2r-2pqs+p^2t}{(p^2+q^2)\sqrt{1+p^2+q^2}}$ [a](Shary, 1991).
Mean curvature, m^{-1}	$H = (k_h + k_v)/2$ (Shary, 1991).
Specific catchment area, m^2m^{-1}	A ratio of an area of an exclusive figure, which is formed on the one hand by a contour intercept with a given point of the landsurface and on the other hand by flow lines coming from higher zones of slope to the ends of this contour intercept, to length of this intercept (Speight, 1968).
Topographic index	$\mathrm{TI} = \ln(\frac{\mathrm{CA}}{G})$ (Beven and Kirkby, 1979).
Stream power index	$\mathrm{SI} = \mathrm{CA} \cdot G$ (Moore et al., 1991).

[a] p, q, r, s and t are partial derivatives of the elevation function $h = f(x,y)$: $r = \frac{\delta^2 h}{\delta x^2}$, $t = \frac{\delta^2 h}{\delta y^2}$, $s = \frac{\delta^2 h}{\delta x \delta y}$, $p = \frac{\delta h}{\delta x}$ and $q = \frac{\delta h}{\delta y}$. p, q, r, s and t can be estimated by the method of Evans (1980).

matter (Moore et al., 1993), content of nitrogen (Aandahl, 1948), calcium, iron, aluminium (Carter and Ciolkosz, 1991), phosphorus (Moore et al., 1993) and natural radionuclides (Martz and de Jong, 1990).

The parent material (C or R) horizon of Vertisols is often clay or shale (Buol et al., 1973; Ahmad, 1983). Some geometric ('topographic') characteristics of a soil horizon surface of this kind can control soil properties (Kachanoski et al., 1985b; Odeh et al., 1991). This is because the surface indicated may be an impermeable layer and hence may affect an intrasoil substance movement. Thus we can anticipate that the C horizon surface of Vertisols may also control to some extent water and solution movement in the soil. To check this proposal it is advisable to use data on quantitative topographic attributes of the C horizon surface, as geometric variables of a surface can describe processes of lateral substance movement along this surface by gravity (see above).

The object of this study is to estimate the effect of overland and intrasoil substance flows on the Vertisol development using concepts of topographic control of lateral substance movement by gravity rather than direct observations

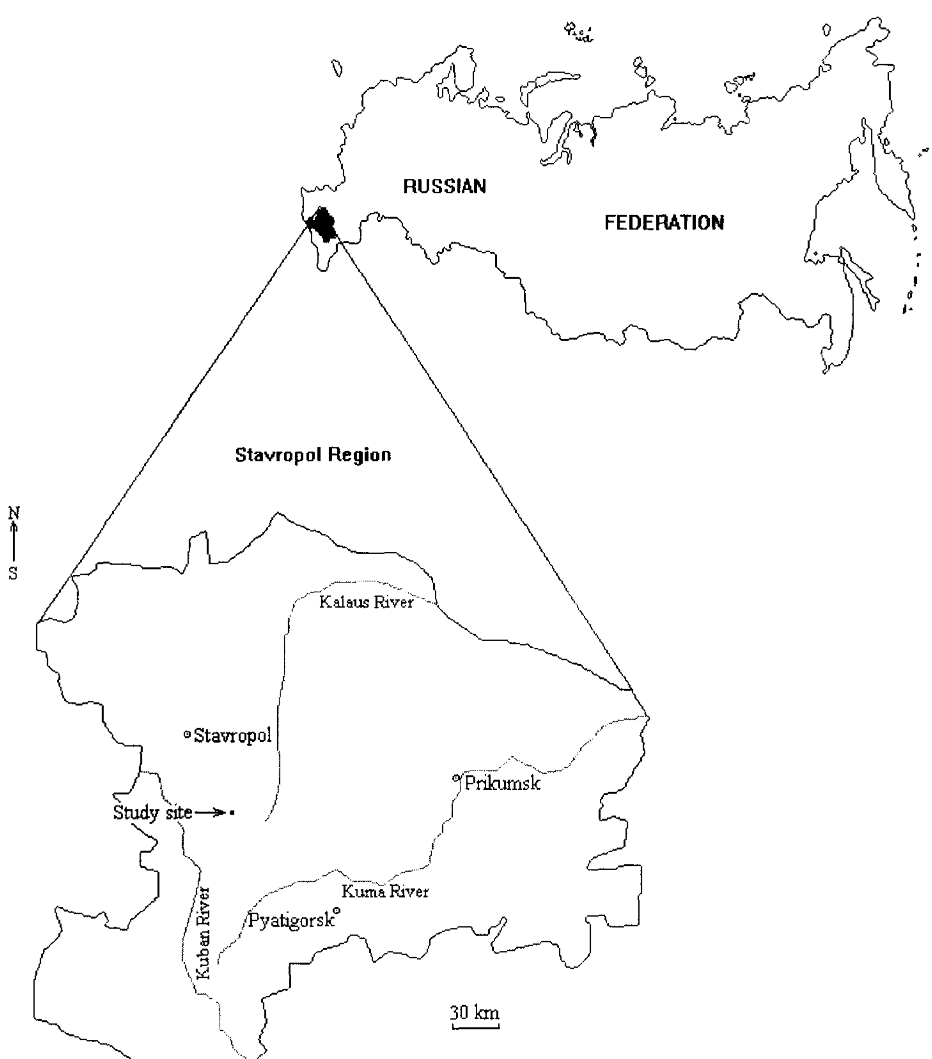


Fig. 1. Geographical location of the study site (44°37′N 42°22′E).

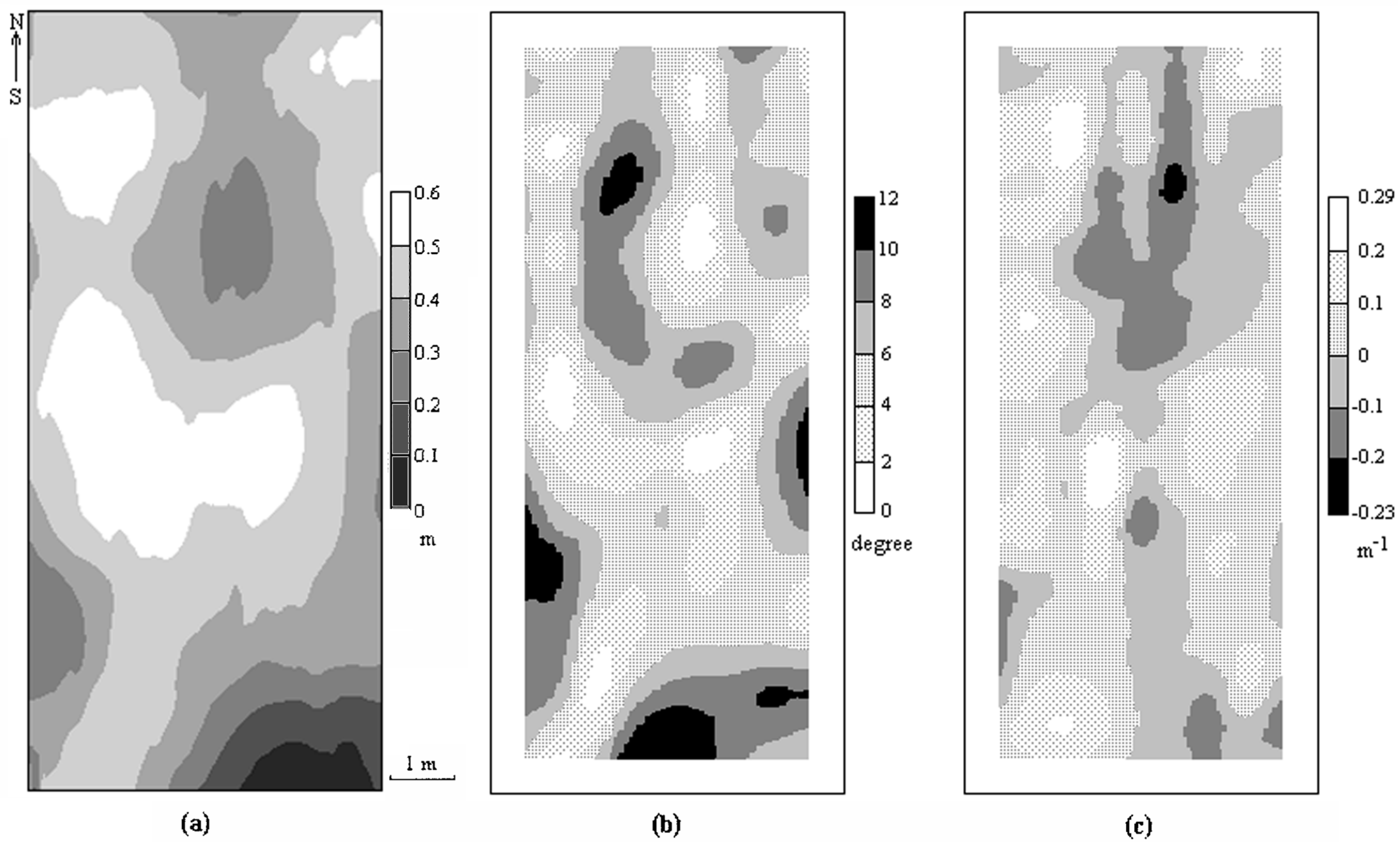


Fig. 2. Maps of the landsurface: (a) elevation, (b) gradient, (c) mean curvature, (d) specific catchment area, (e) topographic index, (f) stream power index (natural logarithmic scales are used for clear mapping of specific catchment area and stream power index).

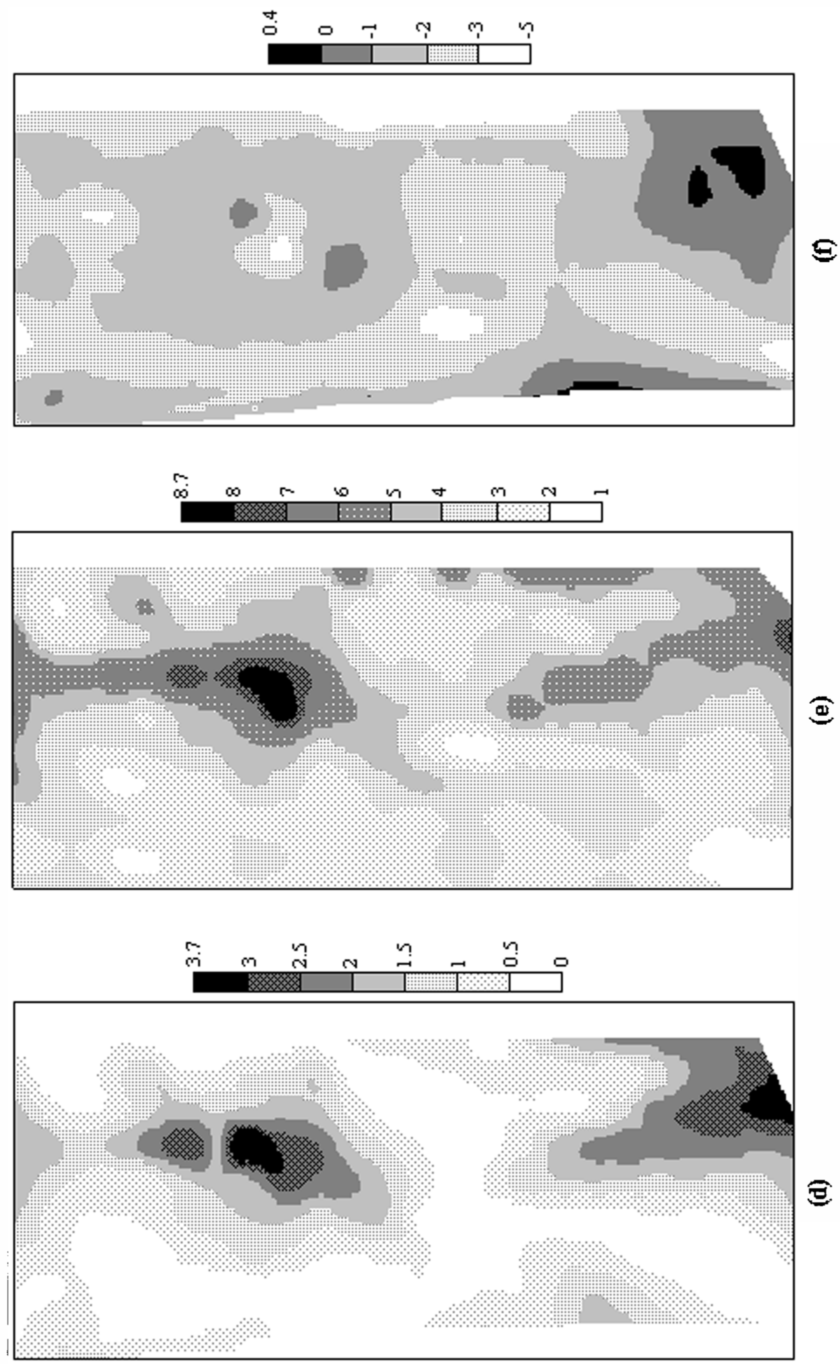


Fig. 2 (continued).

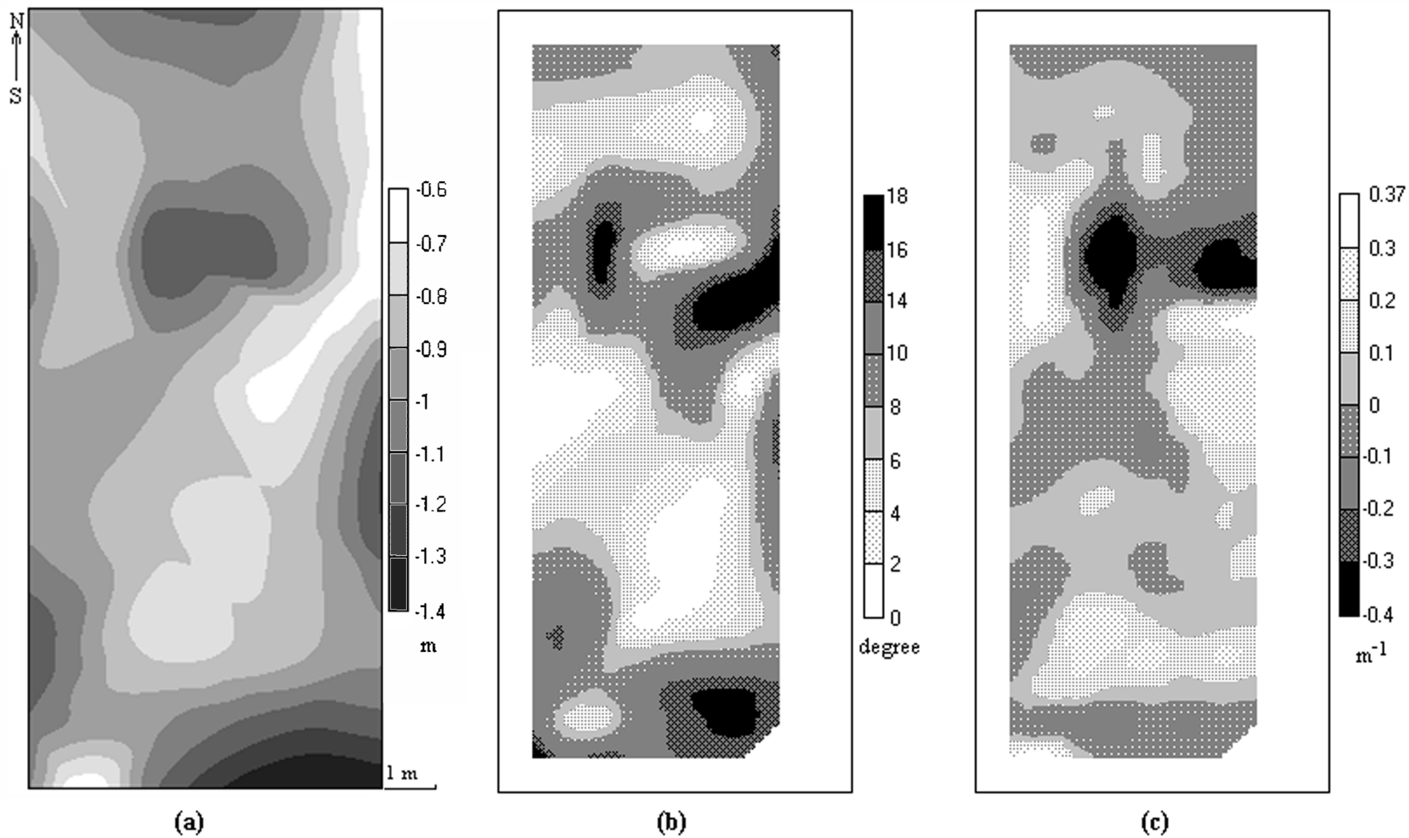
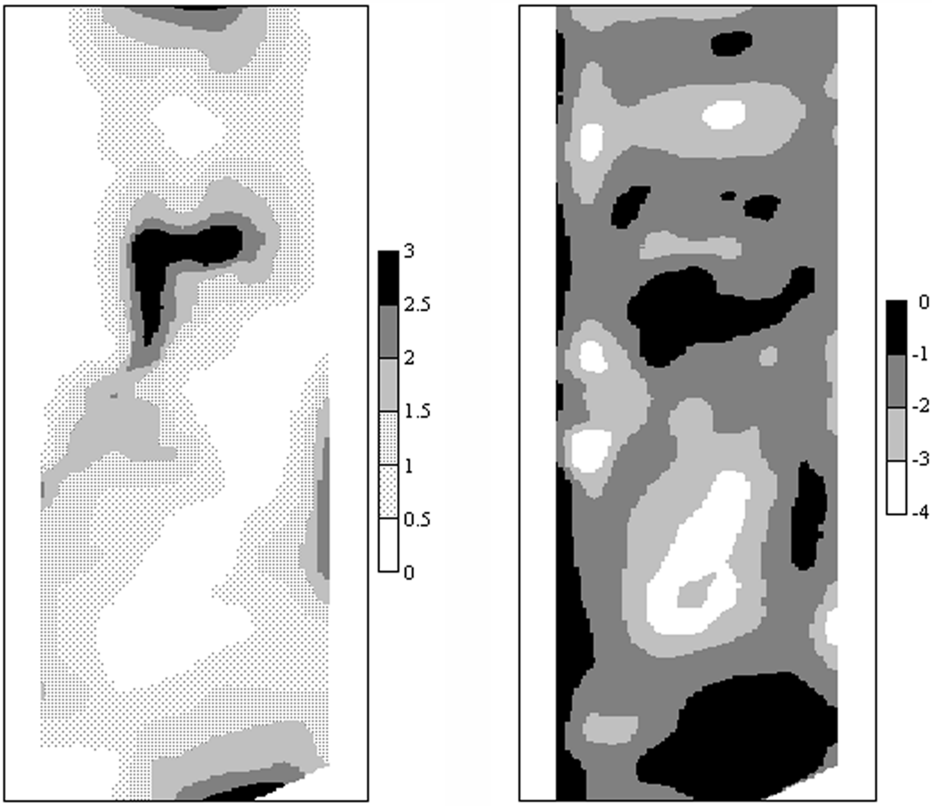


Fig. 3. Maps of the C horizon surface: (a) depth, (b) gradient, (c) mean curvature, (d) specific catchment area, (e) stream power index (natural logarithmic scales are used for clear mapping of specific catchment area and stream power index).



(d) (e)

Fig. 3 (continued).

and measurements of these processes. First, we studied relationships between gilgai microtopographic characteristics and some Vertisol morphological properties such as the C horizon depth and a calcium carbonate-enriched (B_{Ca}) horizon depth. Secondly, we checked the proposal that microtopographic characteristics of the C horizon surface can influence some Vertisol properties by examining the depth to the B_{Ca} horizon surface. During the investigation we used digital models of quantitative topographic variables.

2. Study site

The study site encompasses a part of a gilgai landscape in the south-east part of the Stavropol Upland (Stavropol Region, Russia) (Fig. 1). The study area measures 11.8 × 5.4 m (Fig. 2a).

The study site is located on a gently sloping ledge of a butte-step ouval at an elevation of about 470 m above sea level. The site is characterized by a temperate continental climate. January average temperature is −4°C and July average temperature is 21°C. Precipitation ranges between 450 and 500 mm per year. Parent materials are eluvial marine Neogene clays. Groundwater lies at a depth of more than 10 m (Antykov and Stomorev, 1970).

There is an alternation of micromounds and microdepressions within the gilgai landscape. Microdepressions are located at nodes of a conventional quasi-pentagonal net and at 'pentagon centres'. The elevation difference between a microdepression and a micromound is about 0.4 m. The distance between centres of micromound and microdepression is about 3 m. We categorize this microrelief as a normal gilgai with a large linear distance and a medium amplitude (Hallsworth et al., 1955; Bhattacharjee et al., 1977). The soil complex includes Vertic Meadow–Bog Soils in microdepressions, Vertisols in microslopes, and Vertic Chernozems in micromounds. A detailed description of the soil complex is provided by Kovda et al. (1992). Vegetation cover consists of steppe plants in micromounds, steppe and elements of swamp plants in microslopes, and swamp plants in microdepressions (Kovda et al., 1992).

3. Materials and methods

Initial data were three irregular digital elevation/depth models (DEMs) of the landsurface, the B_{Ca} and the C horizon surfaces. The irregular landsurface DEM (Fig. 2a) was compiled by a field topographic survey. This DEM includes the 364 points surveyed. The irregular DEMs of the C (Fig. 3a) and the B_{Ca} (Fig. 4) horizon surfaces were obtained by an analysis of soil morphological properties using a geological bore with diameter of 0.05 m. The surface of the C horizon was defined as the depth to a soil horizon with yellow colour (Rozanov, 1983). The irregular DEM of this surface consists of the 36 points observed. The surface of the B_{Ca} horizon was determined as the depth to a soil horizon containing carbonate masses with a reaction to 10% HCl (Vadyunina and Korchagina, 1986). The irregular DEM of this surface consists of 67 points observed. Topographic and soil surveys were carried out by the Laboratory of Soil Geochemistry and Mineralogy, Institute of Soil Science and Photosynthesis, Russian Academy of Sciences (Pushchino, Russia).

We constructed all the DEMs in a common relative Cartesian co-ordinate system and in a common local elevation system. The minimal value of the landsurface elevation within the study site was used as the common local datum. So, the landsurface elevation is described by positive values (Fig. 2a), the C horizon depth is represented by negative ones (Fig. 3a), and the B_{Ca} horizon depth is characterized by both negative and positive values (Fig. 4). We converted the irregular DEMs into regular ones by Delaunay triangulation and smooth interpolation (Watson and Philip, 1984). The grid interval of the regular DEMs was 0.5 m.

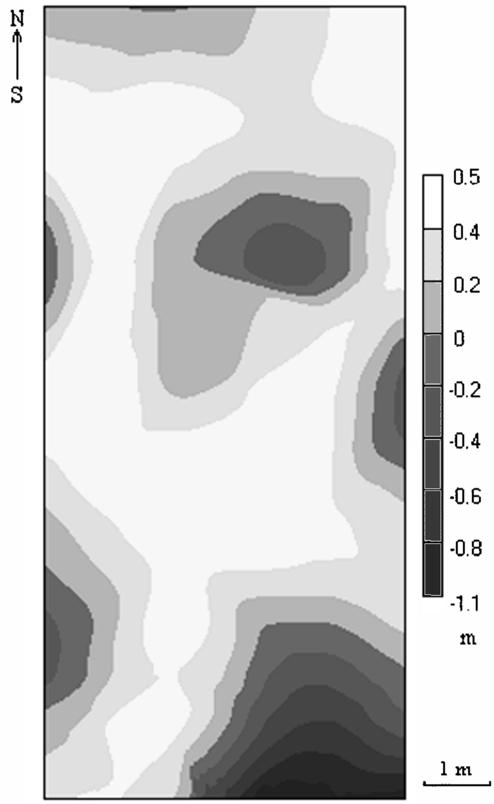


Fig. 4. Map of the B_{Ca} horizon depth.

The very high density of the Vertisol soil profile made hand boring difficult and severely limited. Therefore, the irregular DEMs have dissimilar numbers of observations and hence resolution and elevation accuracy. However, the irregular DEMs are characterized by even distribution of points within the study site. We arranged these DEMs so that nodes of irregular DEM grids cover all typical features of the landsurface microtopography, specifically, microdepressions, microslopes and micromounds. So, we believe that the regular DEMs with a grid interval of 0.5 m represent geometry of all the surfaces adequately. However, some small elements of the B_{Ca} and the C horizon surfaces may be omitted in boring. So, the C (Fig. 3a) and the B_{Ca} (Fig. 4) horizon surface DEMs describe corresponding microreliefs in generalized forms.

Essentially all the topographic variables (Table 1) are connected with several mechanisms and facets of the substance movement along the landsurface by gravity (Section 1). So, we can presume that all of these variables may control to some degree the Vertisol development. Probably, some of topographic attributes can be connected with Vertisol properties to a greater extent than other ones. However, we cannot determine these topographic variables from an

Table 2
Point and interval estimates of pairwise coefficients of correlation of the C and the B_{Ca} horizon depths with landsurface topographic variables

Landsurface topographic variables	C horizon depth			B_{Ca} horizon depth		
	Correlation coefficient	Significance level	95% Confidence interval	Correlation coefficient	Significance level	95% Confidence interval
Elevation (h)	0.68	0.00	0.57–0.77	0.87	0.00	0.80–0.91
Gradient (G)	−0.37	0.00	−0.50– −0.19	−0.42	0.00	−0.56– −0.28
Aspect (ASP)	0.04	0.61	−0.13–0.21	−0.02	0.79	−0.20–0.15
Horizontal curvature (k_h)	0.30	0.00	0.12–0.45	0.38	0.00	0.22–0.51
Vertical curvature (k_v)	0.34	0.00	0.19–0.50	0.25	0.00	0.09–0.41
Mean curvature (H)	0.42	0.00	0.28–0.57	0.43	0.00	0.29–0.58
Specific catchment area (CA)	−0.46	0.00	−0.58– −0.30	−0.61	0.00	−0.72– −0.49
Topographic index (TI)	−0.39	0.00	−0.52– −0.23	−0.48	0.00	−0.60– −0.32
Stream power index (SI)	−0.45	0.00	−0.58– −0.30	−0.78	0.00	−0.83– −0.68

analysis of pre-existing data on topography–soil interrelationships. This is because the topographic control of soil properties has different effects in different soils and terrains. Thus to investigate the microtopographic control of the Vertisol formation it is desirable to use a wide range of topographic attributes such as h, G, ASP, k_h, k_v, H, CA, TI and SI.

Although TI and SI include information on G and CA, and H includes information on k_h and k_v (Table 1), we cannot ignore G, CA, k_h and k_v in our study. The reason is that they are measures of different *simple mechanisms* of the substance movement, while H, TI and SI are *combined attributes* of this process (Section 1). So, for a fundamental understanding the Vertisol development there is a need to analyse both 'simple' and 'combined' topographic attributes.

To obtain digital models of the topographic attributes we used the regular DEMs of the landsurface and the C horizon surface. We calculated digital models of G (Fig. 2b and Fig. 3b), ASP, k_h, k_v and H (Fig. 2c and Fig. 3c) by the method of Evans (1980). To calculate digital models of CA (Fig. 2d and Fig. 3d), TI (Fig. 2e) and SI (Fig. 2f and Fig. 3e) we applied the method of Quinn et al. (1991).

To estimate relationships between the gilgai microtopography and the C horizon depth we performed linear correlation analysis of the C horizon depth with h, G, ASP, k_h, k_v, H, CA, TI and SI of the landsurface. To describe these relationships the 'best' combination of the landsurface topographic variables was chosen by the stepwise linear regression (Aivazyan et al., 1985). To evaluate relationships between the gilgai microtopography and the B_{Ca} horizon depth we carried out linear correlation analysis of the B_{Ca} horizon depth with h, G, ASP, k_h, k_v, H, CA, TI and SI of the landsurface. To check if the C horizon surface influences the Vertisol formation and to estimate this influence we performed linear correlation analysis of the B_{Ca} horizon depth with the depth, G,

Table 3
Point and interval estimates of pairwise coefficients of correlation between the B_{Ca} horizon depth and topographic variables of the C horizon surface

Topographic variables of the C horizon surface	Correlation coefficient	Significance level	95% confidence interval
Depth	0.71	0.00	0.61–0.79
Gradient (G)	−0.56	0.00	−0.66– −0.41
Aspect (ASP)	−0.18	0.03	−0.32–0.00
Horizontal curvature (k_h)	0.36	0.00	0.20–0.50
Vertical curvature (k_v)	0.24	0.00	0.08–0.40
Mean curvature (H)	0.39	0.00	0.23–0.52
Specific catchment area (CA)	−0.41	0.00	−0.56– −0.28
Topographic index (TI)	−0.18	0.00	−0.33–0.00
Stream power index (SI)	−0.63	0.00	−0.73– −0.52

Table 4
Parameters of regression equations describing the dependence of the C horizon depth on landsurface topographic variables and the dependence of the B_{Ca} horizon depth on topographic variables of the landsurface and the C horizon surface

Dependent variables	Independent variables	Coefficients	Significance levels	95% Confidence intervals	R^2
C horizon depth	Elevation (h)	0.84	0.00	0.68–0.99	
	Constant	−1.35	0.00	−1.38 – −1.32	0.46
B_{Ca} horizon depth	Elevation (h)	2.41	0.00	2.03–2.79	
	Landsurface mean curvature (H)	−0.072	0.00	−1.03 – −0.42	
	Landsurface specific catchment area (CA)	−0.009	0.00	−0.01 – −0.003	
	Gradient (G) of the C horizon surface	−0.007	0.1	−0.01 – −0.002	
	Mean curvature (H) of the C horizon surface	0.41	0.00	0.26–0.56	
	Constant	0.16	0.00	0.11–0.21	0.82

ASP, k_h, k_v, H, CA, TI and SI of the C horizon surface. To describe a combined effect of both the landsurface and the C horizon surface on the B_{Ca} horizon depth the 'best' combination of the landsurface and the C horizon surface topographic variables was chosen by the stepwise linear regression (Aivazyan et al., 1985). We used a 142-point sample for correlation and regression analyses.

It should be remembered that *linear* correlation and regression analyses are only the first step in studying the topographic influence on Vertisol properties, because these relationships can be of a nonlinear nature. Moreover, distributions of topographic variables are slightly different from normal law (Evans, 1980), so it is more correct to work not with coefficients but with indices of correlation (Aivazyan et al., 1985). Utilization of partial correlation coefficients is appropriate (Aivazyan et al., 1985), as influences of topographical variables on soil properties can superpose on one another. However, the use of such statistical approaches is outside the scope of the present study.

We applied the software Landlord 2.0 (Florinsky et al., 1995) for the irregular DEM interpolation, topographic variables' calculation and mapping (Figs. 2–4). Correlation and regression analyses were carried out by the software Statgraphics 2.6.

4. Results and discussion

Results of correlation analyses are represented in Tables 2 and 3. Results of regression analyses are shown in Table 4.

Strong correlations of the C (Fig. 3a) and the B_{Ca} (Fig. 4) horizon depths with h (Fig. 2a and Table 2), and the B_{Ca} horizon depth (Fig. 4) with the C horizon depth (Fig. 3a and Table 3) as well as regression equations of the C and the B_{Ca} horizon depths incorporating h (Table 4) reflect some traces of pedoturbation. According to the pedoturbation model (Hallsworth et al., 1955; Buol et al., 1973; Ahmad, 1983), at the final stage of the gilgai development there are oblique and upward movements of subsoil. These movements lead to a rather conformable deformation of soil horizons and the landsurface. A certain parallelism of soil horizon surfaces and the landsurface is necessarily broken down in response to erosion and bioturbation. However, some traces of parallelism are retained.

Nevertheless, variations in the C horizon depth (Fig. 3a) are not dictated by pedoturbation only. We believe that the C horizon depth can be significantly effected by the transport of soil material from micromounds (k_h, k_v and H have positive values, while CA, TI and SI have low values) into microdepressions (k_h, k_v and H have negative values, while CA, TI and SI have high values) as evidenced by correlations of the C horizon depth (Fig. 3a) with k_h, k_v, H (Fig. 2c), CA (Fig. 2d), TI (Fig. 2e) and SI (Fig. 2f) of the landsurface (Table 2).

However, we suppose that soil erosion is of secondary importance to pedoturbation for the C horizon depth. This is demonstrated by the fact that only h appears in the regression equation of the C horizon depth (Table 4), while topographic variables controlling overland substance flows are not involved in this equation.

The B_{Ca} horizon depth (Fig. 4) also does not depend solely on pedoturbation. The B_{Ca} horizon formation can be essentially influenced by two main factors controlling an eluviation of calcium carbonate. It is our opinion that the first factor is dissimilar hydrological regimes at the landsurface micromounds and microdepressions (Kovda et al., 1992) as evidenced by correlations of the B_{Ca} horizon depth (Fig. 4) with H (Fig. 2c), k_h, k_v, CA (Fig. 2d) and TI (Fig. 2e) of the landsurface (Table 2) as well as the regression equation of the B_{Ca} horizon depth incorporating H and CA of the landsurface (Table 4). Indeed, spatial distribution of soil moisture can be specified by k_h, k_v, H, CA and TI (Anderson and Burt, 1978; Beven and Kirkby, 1979; O'Loughlin, 1981; Sinai et al., 1981; Burt and Butcher, 1985; Quinn et al., 1991; Kuryakova et al., 1992). Areas with negative values of k_h, k_v and H, and high values of CA and TI are wetter than areas with positive values of k_h, k_v and H, and low values of CA and TI. Infiltrated water streamlines diverge below landsurface mounds and converge below landsurface depressions (Zaslavsky and Rogowski, 1969). Therefore, the infiltration rate below micromounds is more limited than below microdepressions. So, we believe that the decrease in the B_{Ca} horizon depth can be the result of (a) a diminution of an infiltrated water volume, (b) capillary transport of soil solution from deeper soil horizons to the landsurface, and (c) carbonate precipitation owing to more intensive evaporation in micromounds.

In our opinion, the second factor controlling the eluviation of calcium carbonate is redistribution of intrasoil water and carbonate solution determined by the geometry of the C horizon surface, which functions as an impermeable layer. This is supported by correlations of the B_{Ca} horizon depth (Fig. 4) with H (Fig. 3c), k_h, k_v, CA (Fig. 3d) and TI of the C horizon surface (Table 3) as well as the regression equation of the B_{Ca} horizon depth incorporating H of the C horizon surface (Table 4). However, the intrasoil water and solution movement can be of secondary importance to the influence of overland substance flows for the B_{Ca} horizon formation. This is demonstrated by the fact that the B_{Ca} horizon depth has a lower correlation with topographic variables of the C horizon surface (Table 3) than with the landsurface topographic attributes (Table 2).

It is reasonable to suppose that relative deceleration and acceleration of overland and intrasoil substance flows controlled by k_v (Shary, 1991) are of secondary importance to flow convergence and divergence controlled by k_h (Kirkby and Chorley, 1967) for the B_{Ca} horizon formation. This is shown by the fact that correlations of the B_{Ca} horizon depth with k_h of the landsurface and the C horizon surface are higher than with k_v of these surfaces (Tables 2 and 3). As this takes place, our results indicate that convergence/divergence and deceleration/acceleration of overland substance flows have almost equal effects on variations in the C horizon depth (Table 2). Correlations of the C horizon depth (Fig. 3a) with the landsurface H (Fig. 2c), and the B_{Ca} horizon depth (Fig. 4) with H of the landsurface (Fig. 2c) and the C horizon surface (Fig. 3c) are higher than with relevant k_h and k_v (Tables 2 and 3). The regularity of this kind has been found for soil moisture too (Kuryakova et al., 1992). This is because H combines information on both flow convergence and relative deceleration of flows (Shary, 1995) (Table 1).

Positive correlations of the C horizon depth (Fig. 3a) with the landsurface G (Fig. 2b), and the B_{Ca} horizon depth (Fig. 4) with G of the landsurface (Fig. 2b) and the C horizon surface (Fig. 3b) would have been expected, because G influences flow velocity: the greater G the more intensive a lateral migration of solid and liquid substances (e.g., Young, 1972; Wischmeier and Smith, 1978). So, both accumulation of soil material and water infiltration favouring eluviation of calcium carbonate have to decrease when G increases. However, we have negative correlations of the C and the B_{Ca} horizon depths with G of both surfaces (Tables 2 and 3). This contradiction can be explained by a comparative analysis of maps of G (Fig. 2b and Fig. 3b), k_h, k_v and H (Fig. 2c and Fig. 3c). In some cases, the steeper zones have negative values of k_h, k_v and H, while within flat zones these topographic variables have positive values. Therefore, solid substance, water and solution can be accumulated by flow convergence and relative deceleration, although there is a prerequisite to high flow velocity. In contrast, substances can be washed from a micromound because of flow divergence and relative acceleration, although there is a prerequisite of low flow velocity. In all probability, migration and accumulation of solids and liquids generally depend on H and CA within the study site. This fact can be indicated by the regression equation of the B_{Ca} horizon depth involving H and CA of the landsurface and H of the C horizon surface (Table 4). At the same time, there is some influence of G on lateral substance movement. This is shown by the regression equation of the B_{Ca} horizon depth incorporating G of the C horizon surface (Table 4) as well as strong correlations of the B_{Ca} horizon depth (Fig. 4) with SI of the landsurface (Fig. 2f and Table 2) and the C horizon surface (Fig. 3e and Table 3). Indeed, these correlations are higher than correlations between the B_{Ca} horizon depth (Fig. 4) and CA of both of microreliefs (Fig. 2d and Fig. 3d, Tables 2 and 3), while SI includes information on both CA and G (Moore et al., 1991) (Table 1).

We cannot expect a significant or a strong correlation of the C horizon depth (Fig. 3a) with the landsurface ASP (Table 2), and the B_{Ca} horizon depth (Fig. 4) with ASP of the landsurface (Table 2) and the C horizon surface (Table 3). This is because the vegetation cover dissipates the sunlight at a microtopographic level within the study site. Thus, processes generally controlled by ASP (i.e., insolation, intensity of rain evaporation, snow detention (Zakharov, 1940; Young, 1972)) are independent of a position in the gilgai in this landscape.

The B_{Ca} and the C horizon depths depend, as a rule, more on CA, TI and SI than on k_h, k_v and H of the landsurface and the C horizon surface (Tables 2 and 3). Regularities of this kind were found for properties of other soils (Speight, 1980; Moore et al., 1993) and vegetation cover (Florinsky and Kuryakova, 1996). The reason is that CA, TI and SI take into account a relative location of an area in the landscape (Shary et al., 1991) and hence a relative location of a point in a microcatena. So, in some cases they can better determine topographic prerequisites of lateral substance movement. This is not to say that k_h, k_v and H can be neglected. These two groups of topographic variables are connected with distinct mechanisms and facets of substance movement along the landsurface by gravity (Section 1), and work at different scales (Anderson and Burt, 1980). Therefore, data on CA, TI, SI and k_h, k_v, H can complement each other.

The regression equations obtained explain 46 and 82% of variations in the C and the B_{Ca} horizon depths, respectively (Table 4). We believe that these results are rather good, particularly the R^2 of the B_{Ca} horizon depth equation. This indicates that topography is the main factor controlling the B_{Ca} horizon formation. However, Moore et al. (1993) suggested that possible values of R^2 cannot be more than 70% because of high spatial variability of soil properties. Recall that R^2 derived from regression analysis of topographic variables is in the range from 41 to 68% for soil properties examined in other landscapes (Moore et al., 1993; Bell et al., 1994; Gessler et al., 1995). Our results (Table 4) demonstrate that a better R^2 can be achieved. This fact might suggest that higher values of R^2 can be obtained by decreasing a DEM grid spacing or increasing a DEM resolution (Moore et al., 1993).

The numerical results of our study (Tables 2–4) enable estimation of *the trends* of the actual relationships between the gilgai microtopography and Vertisol properties, and to make approximations of actual dependencies. These results correspond to the resolution and accuracy of the DEMs used. In changing the study scale the character of these dependencies can also change. As landscape, specifically soil cover, has to be viewed in a hierarchical context (e.g., De Boer, 1992) it is essential to use a rank of study scales. Indeed, the chances that an upslope area can contribute to hydrological and geochemical regimes of the study site are good. Unfortunately, we had no data on adjacent terrain. Therefore, the results obtained (Tables 2–4) cannot describe in full measure the actual topographic control of the Vertisol development.

5. Conclusions

1. The dominant mechanism controlling the C horizon depth is pedoturbation. Also, pedoturbation can be important in the development of the B_{Ca} horizons.

2. In all probability, key factors influencing the C and the B_{Ca} horizon depths are overland and intrasoil lateral migration and accumulation of water, solution and solid substances.
3. The C horizon depth depends on the landsurface topographic characteristics, namely: k_h, k_v, H, CA, TI and SI. The B_{Ca} horizon depth is significantly affected by the same topographic attributes of both the landsurface and the C horizon surface.
4. The B_{Ca} and the C horizon depths, as a rule, depend more on CA, TI and SI than on k_h, k_v and H of the landsurface and the C horizon surface.
5. Utilization of topographic variables allows us to explain 82% of variation in the B_{Ca} horizon depth.

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