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Monitoring of Soil Bulk Density in Context with Its Small-Scale Spatial Heterogeneity

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Abstract

The main aim of soil monitoring system is to obtain the knowledge of the most current state and development of soil properties according to concrete threats to soil. To determine the significant changes of soil properties in time, it is important to know spatial variability of concrete soil parameter for concrete site. Only those time changes of the soil parameter are significant, which exceed its spatial variability at the site. The main aim of the study has been focused on the evaluation of small-scale site heterogeneity of equilibrium soil bulk density and the integration of impact of this heterogeneity in evaluation of degradation process of soil compaction in time. As site variation coefficients have considerably varied at standard sampling with five repetitions during monitoring period, one-time detail spatial variability mapping of soil bulk density was realized at 17 repetitions on five selected monitoring sites with different soil type, texture and use. This increase in the number of sampling points helped us to specify and stabilize the values of variation coefficients (between minimum and maximum by standard sampling) as well as the extent of confidence intervals. Standard deviations at the chosen monitoring sites moved from 0.039 to 0.118 $g \cdot cm^{-3}$ in topsoil and from 0.031 to 0.067 $g \cdot cm^{-3}$ in subsoil and expressed as variation coefficient 2.9% - 9.2% and 2.0% - 4.9%, respectively. The intervals of significant time changes of soil bulk density for the sites and depths were determined on the base of its site confidence interval (95%) and uncertainty rate of its measure methodology. The time changes of bulk density values between single year-to-year sampling were overlapped by this interval of significant changes to obtain significant bulk density changes in time. This method allowed us to distinguish significant time changes in soil bulk density from insignificant ones. The bulk density value changes on the monitoring sites were significant in the range of six to nine years within observed period 2002-2014 in both depths.

Keywords

Soil Monitoring, Soil Bulk Density, Spatial, Site and Time Variability,

Significant Time Change

1. Introduction

The main aim of a soil monitoring system is to obtain the knowledge of the most current state and development of soil properties according to concrete threats to soil (Van-Camp et al., 2004; Eckelmann et al., 2006; Kobza et al., 2017). Importance of soil monitoring system consists of providing actual and objective information on temporal trends in important soil properties on agricultural soils. In addition, obtained important current soil outputs are imported to JRC (Joint Research Centre) in Ispra (Italy) and to EEA (European Environmental Agency) in Copenhagen (Denmark). Soil monitoring assesses change in soil properties over time. However, the soil properties are varied both vertically and horizontally.

In soil monitoring is necessary to monitor the trend of changes of soil parameters in context to their spatial heterogeneity. Therefore, it is important to know the spatial variability of single soil parameter for the concrete monitoring site (Širáň & Makovníková, 2011).

Spatial variability of soil properties can be assessed using classical descriptive statistics or geostatistics. Several studies evaluate the spatial variability of the entire spectrum of soil properties and classify individual soil properties into the category by coefficient of variation and nugget ratio (Cambardella et al., 1994; Mzuku et al. 2005; Iqbal et al., 2005; Borůvka, Donátová, & Němeček, 2002; Saldaña, Stein, & Zinck, 1998; Jabro et al., 2010).

The individual soil properties have different spatial variability. Bulk density is one of the basic parameters of the physical state of the soil as well as soil productivity (Lipiec & Stepniewski, 1995; Kristoffersen, & Riley, 2005; Głąb, 2011; Głąb & Gondek, 2013). Bulk density value is also a direct indicator of soil compaction (Thevathasan et al., 2014, Moebius-Clune et al., 2016). Soil compaction determines the potential and consequently the flow of several ecosystem services in agroecosystems, in particular, provisioning services and regulating services (Kizeková et al., 2016; Makovníková et al., 2017a). Bulk density is one of the important input parameters in the organic carbon, nutrient and water stock models (Rawls et al., 2003; Gifford, & Roderick, 2003; Throop et al., 2012; Walter, Don, Tiemeyer, & Freibauer, 2016).

Soil bulk density is dynamic soil property which is variable in space and time. Soil bulk density is changed by crop and land management practices (Soane, 1990; Schipper & Sparling, 2000; Husnjack, Filipović, & Košutić, 2002; Dam et al., 2005; Timm et al., 2006) as well as nature (climate) conditions (Veiga et al., 2008; Alletto & Coquet, 2009) that affect soil cover, soil organic matter, soil structure or porosity (Kumar, Kadono, Lal, & Dick, 2012; Logsdon, 2012; Norman et al., 2016). The process of soil compaction is although reversible, but always tends to achieve an equilibrium state of soil bulk density depending on above-mentioned factors (Linkeš, Makovníková, & Kobza, 1989).

In soil monitoring, it is important to monitor soil properties on representative homogeneous areas with sufficient sampling density. Barrenstein and Leuchs (1991) consider as sufficient areas of up to 400 m^2 for this purpose. However, there is little works in the literature to capture variance of soil parameters on small areas with detailed sampling (Lark et al., 2014).

Lark et al. (2014) recommends sampling a monitoring site (square shape 20 × 20-m^2) by optimizing the arrangement of the collection points using the geostatistic method.

Bulk density is more laborious to measure than many soil properties because a soil sample of known volume must be extracted by a procedure that causes minimal disturbance (Lark et al., 2014; Suuster et al., 2011). Therefore, it is a tendency to sample of a limited number of undisturbed soil specimens or to model its values by pedotransfer functions (Kaur, Kumar, & Gurung, 2002; Heuscher, Brandt, & Jardine, 2005; Benites et al., 2007; Tranter et al., 2007).

However, most of these pedotransfer functions developed for predicting soil bulk density are suitable only for specific agro-pedo-climatic conditions and can be applied only within a limited geographic area (Martin et al., 2009, Makovníková et al., 2017b). In addition, they achieve a higher soil bulk density estimation error than direct measurement methods (Lark et al., 2014).

Lark et al. (2014) states that if we are to choose an appropriate sampling strategy to estimate soil bulk density at a monitoring site then we must consider how variable bulk density is within a site, and we must know how much error is tolerable in the final estimate. When analyzing the development of monitored parameters in soil monitoring and determining their significant change, it is important to know the spatial variability of an individual parameter on a given site. The differences in space should not be exchanged for the irreversible developmental changes in time.

The main aims of the study were 1) to evaluate the small-scale spatial heterogeneity of soil bulk density and 2) to integrate the impact of the small-scale heterogeneity in evaluation of degradation process of compaction, incorporating the applicable criteria that follow.

2. Material and Methods

2.1. Monitoring Sites

For purpose of this paper, five monitoring sites were chosen, that are a part of Slovak soil monitoring. They are localised in the central part of Slovakia. Sampling sites represent main soil types and subtypes of Slovakia (**Table 1**).

Site Liesek, Haplic Stagnosol (Siltic, Eutric) developed on flysh, used as permanent grasland, is located on the terraces of the river. Grassland was cutted in spring (hay production), then was grazed.

Site Koš, Haplic Planosol (Albic, Eutric, Siltic), used as arable soil, is situated in Uper Nitra basin. At the time of soil sampling the oilseed rape was grown here.

Table 1. Selected soil characteristics on evaluated monitoring sites.

Site	Soil depth	Soil texture[a]				Humus content %
	m	Clay %	Silt %	Sand %	Texture class	
Koš	0.10 - 0.20	23	60	17	silty loam	medium
	0.30 - 0.40	39	53	8	silty clay loam	low
Liesek	0.10 - 0.20	28	35	37	loam	medium to high
	0.30 - 0.40	33	38	29	clay loam	low
Istebné	0.10 - 0.20	21	31	48	loam	low to medium
	0.30 - 0.40	24	26	50	loam	low
Sihla	0.10 - 0.20	12	42	46	loam	high
Dvorníky	0.10 - 0.20	19	50	31	silty loam	low
	0.30 - 0.40	18	49	33	silty loam	very low

a. FAO (USDA) classification: clay < 0.002 mm, silt 0.002 - 0.05 mm, sand 0.05 - 2.00 mm.

Site Istebné, Stagnic Cambisol (Siltic, Eutric), used as arable soil, is located in Veličianska valley. At the time of soil sampling the temporary clover-grass mixes (in the fourth year after cultivation) was grown.

Site Sihla, Haplic Cambisol (Skeletic, Dystric), developed on acid rocks, used as permanent grassland (alternating cutting and grazing) is placed in the Vepor Mountains.

Site Dvorníky, Gleyic Fluvisol (Siltic, Eutric), used as arable soil, is located in alluvial flat of Štiavnica river. At the time of soil sampling the oats was grown here.

2.2. Soil Sampling

Monitoring site represents the circular shape, with a diameter 20 m and an area of 314 m^2 (Kobza et al., 2019). Soil bulk density sampling on selected sites was realized within months May-June (depending on weather condition) when the soil is naturally compacted and has achieved condition that changes just slightly by natural impacts, thus bulk density is near equilibrium state (mainly in the case of arable soils). As standard monitoring sampling, undisturbed soil samples are taken in depths 0.10 - 0.20 m and 0.30 - 0.40 m in five repetitions. The coefficients of variation for soil bulk density obtained by standard sampling (5 locations) considerably fluctuated at sites in the individual years of monitoring period. Therefore, detailed sampling with 17 repetitions was performed in order to specify and stabilize the values of variation coefficients and to obtain more real spatial (site) variability of soil bulk density of five monitoring sites The samples were taken in centre and in 5 m and 10 m distance from centre of each site in eight directions of cardinal points in two depths 0.10 - 0.20 m and 0.30 - 0.40 m (**Figure 1**).

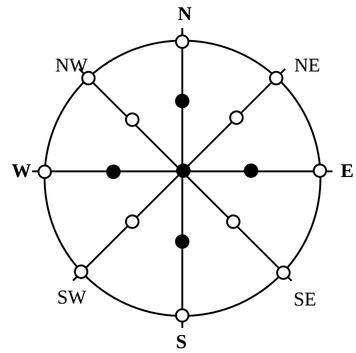

Figure 1. Scheme of the site sampling (detailed sampling: all 17 points, standard sampling: 5 black points).

At each sample location the soil was taken by auger with a cylinder of diameter 61 mm and a volume of 100 cm^3. On return to the laboratory, the cylinders were weighed, and then placed in an oven to dry at 105˚C for 8 hours or till achieving of constant weight. After drying, the samples were reweighed and the dry soil bulk density was calculated for each sample (Kobza et al., 2011).

3. Results and Discussion

To determine the real spatial variability of monitoring sites, the data of soil bulk density (D_b) obtained by the detailed sampling (17 location) were statistically analyzed and are shown in **Table 2**. The lower bulk density value is in the topsoil compared to subsoil on the all monitored sites (site Sihla—measured only in the topsoil) and also during whole evaluated monitoring period (**Table 3**). This finding corresponds with other authors (Lark et al., 2014; Suuster et al., 2011; Tranter et al., 2007) and it is caused by the changing of some soil properties with soil depth (content of SOC, clay, silt, sand). The highest D_b value in deeper soil layers can be explained as influence of the mechanical stress caused by overburdened soil (Heuscher et al. 2005) and by the formation of plough-pan layer (often at a depth of 25 cm) (Alakukku et al., 2003). Suuster et al. (2011) states D_b increase to a sampling depth of 40 cm, then D_b start to decrease. No tillage and reduced tillage systems increases D_b of soil layers (5 - 20 cm) located closer to the soil surface (Schipper & Sparling, 2000; Husnjack, Filipović, & Košutić, 2002). For topsoil, average D_b values moved in range of 1.153 to 1.434 $g{\cdot}cm^{-3}$ and these are higher for cropland soils (Koš and Istebné site) compared to grassland soils (Liesek and Sihla site). Within the subsoil, means of D_b ranged in interval 1.383 do 1.539 $g{\cdot}cm^{-3}$ and was higher at the texturally differentiated soils (Koš and Liesek site) that have higher clay content in deeper soil layers over which the precipitation water stagnates and supports an increase of D_b. Finally, the least D_b value was recorded in the Sihla site topsoil (1.065 $g{\cdot}cm^{-3}$) and the highest in the subsoil of Stagnosol in the Koš site (1.638 $g{\cdot}cm^{-3}$). D_b values on our sites (soil texture in range loam to clay loam) increased with increase of the clay content (r = 0.81) and with decrease of humus content (r = −0.84) and sand

Table 2. Summary statistics for spatial data of soil bulk density (in g·cm^{-3}) on chosen monitoring sites obtained by detailed sampling.

Site	Soil depth m	Min	Mean	Max	Standard deviation	Variation coefficient %	Count	Shapiro-Wilk test
Koš	0.10 - 0.20	1.342	1.434	1.539	0.060	4.2	17	0.922
	0.30 - 0.40	1.482	1.539	1.638	0.037	2.4	17	0.940
Liesek	0.10 - 0.20	1.209	1.312	1.415	0.067	5.1	17	0.940
	0.30 - 0.40	1.486	1.534	1.605	0.031	2.0	17	0.936
Istebné	0.10 - 0.20	1.282	1.357	1.423	0.039	2.9	17	0.964
	0.30 - 0.40	1.370	1.464	1.590	0.061	4.2	17	0.972
Sihla	0.10 - 0.20	1.065	1.153	1.282	0.056	4.9	17	0.961
Dvorníky	0.10 - 0.20	1.115	1.288	1.519	0.118	9.2	17	0.940
	0.30 - 0.40	1.255	1.383	1.483	0.067	4.8	17	0.963

Table 3. Summary statistics for time data of bulk density (D_b, g·cm^{-3}) and its variation coefficients (%) on chosen monitoring sites for single years during soil monitoring period 2002-2014.

Site	Soil depth m	n	Soil bulk density (D_b), g·cm^{-3}					Site CV% of D_b[c]			CV% for SS[d] in year of DS	CV% for DS[e]
			Mean	Min	Max	CV%[a]	% of mean[b]	Mean	Min	Max		
Koš	0.10 - 0.20	13	1.391	1.226	1.605	6.6	105	4.3	2.2	6.0	5.1	4.2
	0.30 - 0.40	13	1.553	1.442	1.616	3.0	100	2.4	0.5	6.4	0.7	2.4
Liesek	0.10 - 0.20	13	1.389	1.320	1.442	2.8	99	2.8	0.5	7.6	1.5	5.1
	0.30 - 0.40	13	1.551	1.455	1.703	4.3	100	2.8	1.6	4.5	2.5	2.0
Istebné	0.10 - 0.20	12	1.391	1.202	1.487	5.9	96	5.3	1.4	9.5	5.7	2.9
	0.30 - 0.40	12	1.544	1.468	1.621	3.5	95	3.3	1.0	8.2	8.2	4.9
Sihla	0.10 - 0.20	3	1.180	1.120	1.240	5.1	95	4.9	4.3	5.8	5.8	4.9
Dvorníky	0.10 - 0.20	13	1.249	1.143	1.334	5.3	99	6.7	1.4	12.4	8.2	9.2
	0.30 - 0.40	13	1.351	1.218	1.433	5.5	102	3.0	0.4	7.5	5.8	4.8

a. CV%: coefficient of variation of monitored period, b. % of mean: standard sampling performed in the year of detail sampling in relation to D_b mean of monitored period, c. Site CV% of D_b: from standard sampling performed in single years, d. SS: standard sampling (5 repetitions) used in single years, e. DS: detail sampling (17 repetitions).

content (r = −0.53). Tranter et al. (2007) suggested that negative correlation between SOC and D_b is the result of soil aggregation. Correlation between D_b and soil texture resp. SOC content is in good agreement with previous studies and it is used to create different models in order to obtain an estimate of D_b or other soil properties (Heuscher, Brandt, & Jardine, 2005; Suuster et al., 2011; Bernoux et al., 1998).

For the purpose of this contribution, characteristics of variability (standard deviation, coefficient of variation—CV; Table 1) obtained at monitoring sites are more important. The values of the standard deviation ranged from 0.039 to 0.118 g·cm^{-3} in topsoil, and from 0.031 to 0.067 g·cm^{-3} in the subsoil, expressed by the coefficient of variation 2.9% - 9.2% and 2.0% - 4.8%, respectively. In terms of the variation coefficient values, soil properties can be classified into three categories as low (0% - 15%), medium (15% - 75%) and high (>75%) spatially variable. According to several studies from different localities with different soil type and texture, area size and sampling density, the values of coefficients of variation ranged from 3.8% - 17% and classify D_b as a soil property with low spatial variability (Cambardella et al., 1994; Mzuku et al. 2005; Iqbal et al., 2005; Borůvka, Donátová, & Němeček, 2002; Jabro et al., 2010; Veiga et al., 2008). Kutílek et al. (2000) ranks the soil bulk density as the littlest varying in comparison with the other soil physical properties. Its variation coefficient is less than 15% within pedotop on area of a several hectares and in a morphogenetic homogeneous soil. Lark et al. (2014) recorded CV value 9.1% in topsoil and 10.7% in subsoil for loamy Luvisol (with clay-enriched subsoil) by detailed sampling of 20 × 20 m^2 monitoring site (90 locations in three transect).

Variation coefficient values are higher (approximately twice) in topsoil compared to subsoil. The Istebné site is an exception because its state is the opposite (topsoil 2.9%, subsoil 4.2%). This may be the effect of a specific cultivation regime. Four-year temporary clover-grass stand was grown at this site in time of detailed sampling, established after ploughing the original one. The soil into depth of plough was aerated, enriched with organic matter supporting the activity of the numerous earthworms present here and stabilized by the clover roots. The 50% share of the sand fraction and the weathered sandstone fragments also contribute to the aeration and spatial heterogeneity of soil. In the year of detailed sampling at this site, the D_b value was below the average of evaluated monitoring period (95% of mean) and highest variation coefficient of this period was found in subsoil according standard sampling (**Table 3**). During the monitoring period 2002-2014, these higher variation coefficients in subsoil were recorded in sites Istebné (in 3 cases), Koš (in 3 cases) and Liesek (in 8 cases) while in the year of detailed sampling it was measured in Istebné and Liesek but this was confirmed by detailed sampling only in Istebné.

In the case of soil types, the highest values of variation coefficient were found in Fluvisol at the Dvorníky site (topsoil 9.2%, subsoil 4.8%). In other localities, its values in topsoil ranged from 4.2% to 5.1% and in subsoil from 2.0% to 2.4%. Overall, the lowest coefficient of variation was recorded in the subsoil of Stagnosol in Liesek (2.0%) and the highest in the topsoil of Fluvisol in Dvorníky (9.2%). This corresponds with the findings of Saldaña et al. (1998) who report a decrease in variability of soil properties from young (our Fluvisol) to old (our Stagnosol and Planosol) deposits and soil homogenisation in time.

Time data of soil bulk density (standard sampling) on chosen monitoring sites for single sampling years during soil monitoring period 2002-2014 are given in **Table 3**. On average, D_b for the whole evaluated monitoring period confirm the increase of D_b with depth. Variation coefficients expressing D_b deviations of individual years from the average of the whole period ranged from 5.1% to 6.6% in the topsoil of the monitored localities (except Liesek with 2.8%) and from 3.0% to 5.5% in subsoil. Detailed sampling at the localities was carried out mostly at the level of the long-term average, with the exception of Cambisols in Istebné and Sihla (at a lower D_b compared to the long-term average) and topsoil of Stagnosol in Koš (at a higher D_b).

Variation coefficients at observed sites varied considerably from year to year which is shown at their min and max values. Comparing variation coefficients of standard and detailed sampling, their values at standard sampling were mostly overestimated. Variation coefficients obtained by detailed sampling were between minimal and maximal values of evaluated monitoring period (standard sampling in single years) at the all sites and depths. The increase in the number of sampling points from the site eliminated the randomness of D_b estimate and it was discovered more real variability which considerably varied at smaller number of repetition (Table 3).

The spatial variability of soil bulk density at the monitoring sites was used as a basis for defining the interval of significant changes in developmental time series. Within sites, a two-sided confidence interval for the arithmetic mean of the normal distribution was determined at the 95% probability level (Table 4). Then, the interval of significant time changes of soil bulk density for time series was created on the basis of a two-sided site confidence interval for the mean value at given depths and the degree of uncertainty of analytical determination of soil bulk density values.

The significant time changes in bulk density values over time were obtained by overlapping the changes of soil bulk density in time series (year-to-year changes in soil bulk density, its change against previous year) with a calculated interval of significant time changes (Figures 2-5). The bulk density value changes on the monitoring sites and depths were significant in the range of six to nine years within observed period 2002-2014. The most cases of significant negative changes were observed on locality Koš (topsoil-5, subsoil-5) while the least ones on locality Dvorníky (topsoil-4, subsoil-3). Insignificant changes were monitored in three to seven years of evaluated period.

Table 4. Site confidence intervals for data of soil bulk density ($g \cdot cm^{-3}$) on evaluated monitoring sites as base for determination of intervals of significant time changes.

Site	Soil depth m	Site confidence interval $g \cdot cm^{-3}$		Interval of significant time changes $g \cdot cm^{-3}$
Koš	0.10 - 0.20	1.405 - 1.462	1.434 ± 0.029	±0.039
	0.30 - 0.40	1.521 - 1.557	1.539 ± 0.018	±0.028
Liesek	0.10 - 0.20	1.280 - 1.344	1.312 ± 0.032	±0.042
	0.30 - 0.40	1.520 - 1.549	1.534 ± 0.015	±0.025
Istebné	0.10 - 0.20	1.338 - 1.376	1.357 ± 0.019	±0.029
	0.30 - 0.40	1.435 - 1.493	1.464 ± 0.029	±0.039
Sihla	0.10 - 0.20	1.126 - 1.180	1.153 ± 0.027	±0.037
Dvorníky	0.10 - 0.20	1.232 - 1.345	1.288 ± 0.056	±0.066
	0.30 - 0.40	1.351 - 1.415	1.383 ± 0.032	±0.042

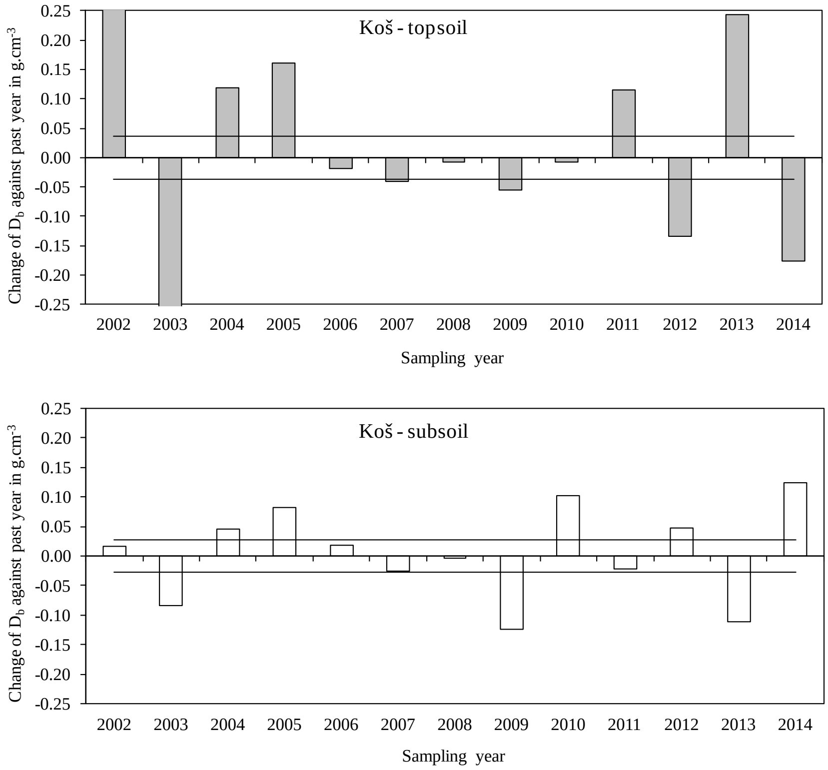

Figure 2. Year-to-year time changes (bars) of soil bulk density (D_b, in g·cm^{-3}) in relation to interval of significant time changes (lines) at the Koš site (topsoil and subsoil).

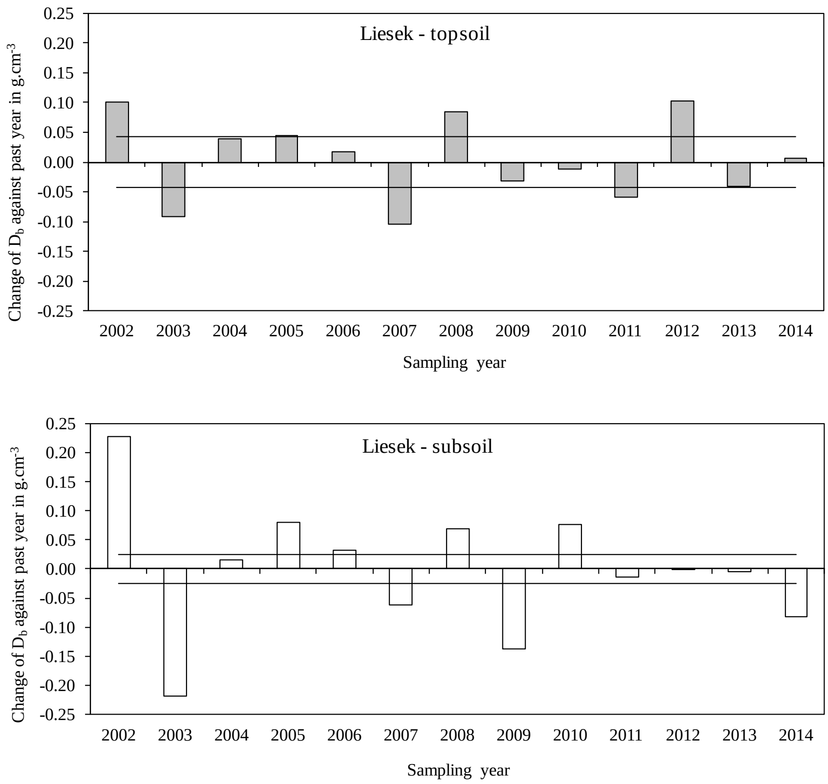

Figure 3. Year-to-year time changes (bars) of soil bulk density (D_b, in g·cm^{-3}) in relation to interval of significant time changes (lines) at the Liesek site (topsoil and subsoil).

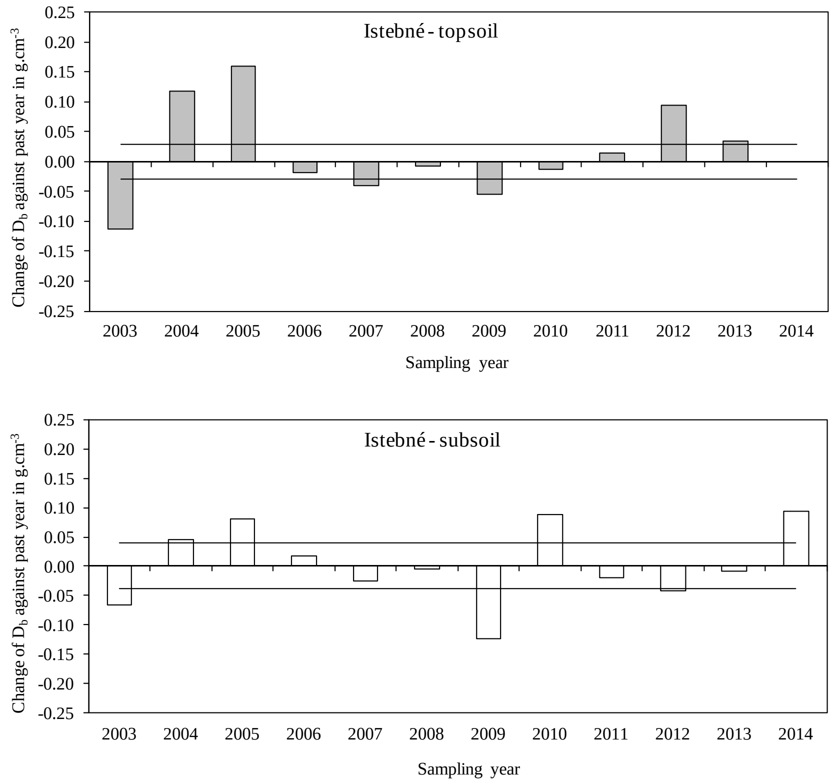

Figure 4. Year-to-year time changes (bars) of soil bulk density (D_b, in g·cm^{-3}) in relation to interval of significant time changes (lines) at the Istebné site (topsoil and subsoil).

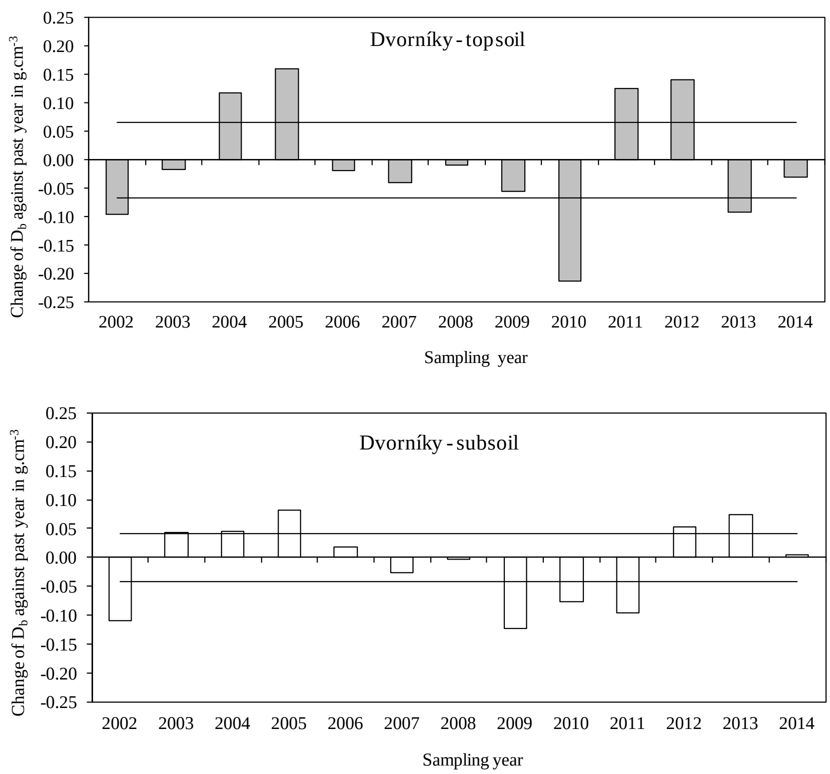

Figure 5. Year-to-year time changes (bars) of soil bulk density (D_b, in g·cm^{-3}) in relation to interval of significant time changes (lines) at the Dvorníky site (topsoil and subsoil).

4. Conclusion

This study allows us to draw specific conclusions about the detailed sampling results for determination of soil bulk density and its spatial variation only for monitoring sites with soils comparable to those at our five sites. Sampling a monitoring site at 17 points gives a mean value of soil bulk density in the topsoil and subsoil with variation coefficients of less than 5% excluding the locality Dvorníky (topsoil—9.2%). Detail sampling with increase of repetitions allowed us to stabilize the variation coefficient values of soil bulk density at the monitored sites and to create the interval of significant time changes. The changes in soil bulk density smaller than this interval cannot be considered as significant, because they did not exceed the degree of heterogeneity of the monitoring site. The bulk density value changes on the monitoring sites and depths were significant in the range of six to nine years within observed period 2002-2014 in both depths. The most cases of significant negative changes were observed on locality Koš (topsoil-5, subsoil-5) and the least on locality Dvorníky (topsoil-4, subsoil-3).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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