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Impact of short- and long-term agricultural use of chernozem on its quality indicators

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A b s t r a c t. The impact of 5, 45, and 75 year agricultural use of a clayey loam Haplic Chernozem on its selected quality indicators was determined. Contents of soil organic matter and microbial biomass carbon were equal to 43.1±2.2 g C kg^{-1} soil and 480.0±67.6 mg C kg^{-1} soil in the fallow land. Soil organic matter content in the agricultural soils ranged from 30.2±1.8 (75 year plot) to 47.5±2.1 g C kg^{-1} soil (5 year plot), while microbial biomass carbon content varied from 340.2±5.9 (75 year plot) to 371.2±10.2 mg C kg^{-1} soil (5 year plot). Among the three agricultural treatments, only the 75 year one resulted in a significant decline in total amounts of water-stable aggregates (70.8±8.2%) and clay content (26.9±1.0%), compared to those parameters in the fallow land (90.1±9.4% and 30.5±1.2%, respectively). Distribution of the minimum values of differential entropy of water vapour adsorption in the soil also showed that the 75 year agricultural management unfavourably affected the thermodynamic state of soil solid phase.

K e y w o r d s: agricultural use of soil, soil quality, organic matter, aggregation, thermodynamic characteristics

INTRODUCTION

The capacity of soils for maintaining their high quality is dependent on soil resistance and resilience under given environmental and anthropogenic impacts (Schjonning *et al.*, 2004; Seybold *et al.*, 1999; Szabolcs, 1994). Basically, soil resistance refers to 'the capacity of a system to continue to function without change through a disturbance' (Pumm, 1984). Key factors controlling the soil resistance are soil texture and mineralogical composition, soil bulk density and strength, soil organic matter (SOM) and water-stable aggregates (WSA) (Czyż and Dexter, 2009). Resilience is considered to mean 'the capacity of a population (or system) to return to an equilibrium following displacement in response to a perturbation' (Swift, 1994). Soil processes, such as chemical and physical buffering, accumulation and humification of organic matter, formation and stabilization of soil structure, swelling, and fixation of nutrients, are responsible for maintaining the required soil resilience.

During the last two decades, particular attention of scientists has been focused on two directions of multidisciplinary studies of selected quality indicators of soils. The first direction of the research was to quantify the thermodynamic characteristics of soil solid phase. The results of those studies showed significant differences in:

- water vapour and nitrogen adsorption energy of different soil clay minerals, soil types (Józefaciuk and Bowanko, 2002), soil organic matter content (Sokołowska *et al.*, 1993) and soil tillage (Józefaciuk *et al.*, 2001);
- surface free energy of soil minerals enriched with different rates of humic acid (Hajnos, 2004);
- differential molar entropy and heat of water vapour adsorption of clay fractions from different soil horizons (Raytchev *et al.*, 2005).

These thermodynamic characteristics of the soil solid phase can be very useful when determining the equilibrium and direction of soil formation/degradation processes. Therefore, the above-mentioned results on adsorption energy and differential molar entropy of water vapour adsorption by soils can be considered as a basis for further studies of short- and long-term soil agricultural use.

The second direction of scientific interests combined traditional studies on the effects of different tillage, fertilizers and farming systems on SOM and its labile forms as related to maintaining optimal water-stable aggregation as a key indicator of soil quality (Dąbek-Szreniawska *et al.*, 2002; De Gryze *et al.*, 2005; Simansky *et al.*, 2008). Continuous soil agricultural management can unfavourably affect the processes of SOM microbial transformation, water-stable aggregation, and synthesis of soil minerals (Ananyeva *et al.*, 1999; Dąbek-Szreniawska *et al.*, 2002; Norton *et al.*, 2006; Reganold *et al.*, 1987) and, as a result, may lead to soil degradation *ie* an irreversible loss of soil resistance and

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resilience. Therefore, there is a need to identify soil management thresholds as the boundaries between sustainable and unsustainable soil quality indicators (Gomez *et al.*, 1996). Multidisciplinary studies of thermodynamic, microbial and structural characteristics of soils can be a useful tool to evaluate whether traditional and new agricultural management practices are able to maintain the soil quality during short- and long-term periods.

The aim of the present studies was to quantify the influence of 5, 45, and 75 year agricultural use of a clayey loam Haplic Chernozem on its selected quality indicators.

MATERIALS AND METHODS

Four plots were selected in the Kamennaya Steppe Preserve (51°01' N, 40°43' E) located ~200 km SE Voronezh city (Central Federal District of Russia). Mean annual temperature of the area is 6.6°C and precipitation is 507.7 mm (Sentsova, 2002). The soil was classified as a clayey loam Haplic Chernozem (FAO classification). Soil moisture content reaches field capacity only during late spring, while a drought is usually observed in summer (Torn *et al.*, 2002). Disturbed composite soil samples, consisting of 8-9 subsamples, were collected in mid-summer from a 20 cm topsoil of a fallow land with perennial grasses (*Festuca valesiaca* Gaud.) and three experimental plots of the Dokuchaev Institute of Agriculture in the Central Chernozem Region of Russia. By the time of soil sampling the agricultural plots had a total duration of agricultural use of 5, 45 and 75 years, and had been used mainly for growing grain cereals and vegetables (Tcheverdin and Dorokhin, 2009). These plots were tilled annually with a mouldboard or mouldboardless plough to 20-22 cm depth.

A detailed description of methods for measurements of total amount and distribution of size fractions of WSA, SOM and MBC content, and basal respiration (BR) was presented in our previous paper (Balashov *et al.*, 2010).

Differential entropy of water vapour adsorption is one of the important thermodynamic characteristics of a soil solid phase (Raytchev *et al.*, 2005). Values of the differential entropy are represented as a difference between the entropy of adsorbed water and the entropy of pure water (Cary *et al.*, 1964; Gregg and Sing, 1982). To determine the differential entropy of water vapour adsorption of the clayey loam Haplic Chernozem, a vacuum chamber method was used and isotherms of water vapour adsorption were measured by a gravimetric method (Sokołowska *et al.*, 2004; Vadjunina and Korchagina, 1986). Before the measurements of adsorption isotherms, air-dried whole soil samples (1 g), preliminary passed through a 1 mm sieve, were placed into open glass vials and kept in a hermetically closed vacuum chamber with concentrated sulphuric acid until the mass of all the soil samples reached constant values. Afterwards, the soil samples were subsequently kept in separate vacuum chambers with increasing relative water vapour pressures (from 0.10 to 0.98) at 298 and 303 K until the mass of all soil samples also showed constant values. The relative water vapour pressures in the vacuum chambers were created by saturated solutions of different salts ($ZnCl_2$, $CaCl_2$, NaCl, NH_4Cl, KCl, K_2SO_4). All the soil samples were dried at 105°C for the determination of moisture content. The values of differential entropy of water vapour adsorption (dS°) by the whole soil samples were calculated using the adsorption isotherms:

$$dS^\circ = -\frac{R}{2M}(\ln f_1 f_2) + \frac{T_1 + T_2}{T_2 - T_1}\left(\ln \frac{f_1}{f_2}\right),$$

where: R is the universal constant, M is the molecular mass of water, f_1 and f_2 are the relative water vapour pressures at temperatures of T_1 (298 K) and T_2 (303 K).

All the measurements of the soil properties were done in three replicates. Means and standard deviations were calculated for each parameter within each treatment. Significance of differences between treatments was estimated by analysis of variance (one-way ANOVA) at $p \leq 0.05$. Relationships between the soil parameters were assessed with a linear regression analysis using a computer statistical package.

RESULTS AND DISCUSSION

The results of our studies showed that the 5 and 45 year periods of agricultural use caused only an insignificant decrease in the total amount of WSA, to 83.0±3.8 and 86.6±8.9% compared to 90.1±9.4% in the fallow land (as a reference soil). However, the 75 year agricultural management of the soil resulted in a significant (p=0.05) decline in the total amount of WSA to 70.8±8.2% (Fig. 1).

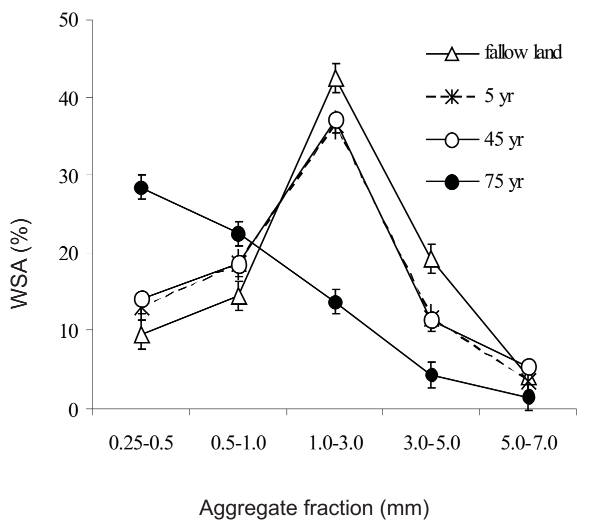

Fig. 1. Distribution of water-stable aggregate size fractions (WSA, %) of a clayey loam Haplic Chernozem on plots with fallow land and 5, 45 and 75 year agricultural management. Vertical bars are standard deviations (at $p \leq 0.05$ and n = 3).

Changes in distribution of separate size fractions of WSA also reflected different effects of 5, 45, and 75 year agricultural use on the structural state of the soil.

The distributions of 0.25-7.0 mm WSA fractions showed a similar pattern in the soil of fallow land and in the 5 and 45 year agricultural plots, despite the significant ($p \leq 0.05$) differences in the amounts of these WSA fractions between the treatments.

Compared to these three treatments, the 75 year soil management resulted in another pattern of the distribution of WSA size fractions. Firstly, a significant ($p<0.001$) increase was observed in the amount of 0.25-0.5 mm WSA fractions and, secondly, a significant ($p \leq 0.001$) decrease was determined in that of 1.0-7.0 mm WSA size fractions in the soil with the 75 year agricultural use. Our results are supported by the data of Tikhonravova (2009) who reported that 70 year use of the same soil on another agricultural plot had led to a similar pattern of distribution of WSA size fractions.

In our studies, the observed decline in the amount of larger WSA fractions (1.0-7.0 mm) did not result in any additive increase in the amount of smaller WSA fractions (<1.0 mm) in the soil of the 75 year old plot. This discrepancy could be attributed to an irreversible destruction of WSA because of the losses of clay particles (Norton *et al*., 2006), SOM and its labile forms (Dąbek-Szreniawska *et al*., 2002).

Our data on the amount of clay particles (<0.001 mm) in the soil probably supported this explanation. Clay content in the whole soil samples reached 30.5±1.2% in the fallow land and 30.8±1.1% in the 45 year old agricultural plot, while the soil from the 75 year one had a significantly ($p=0.01$) lower content of clay (26.9±1.0%).

The soil organic matter content in the whole soil samples was equal to 43.1±2.2 g C kg^{-1} soil (fallow land), 47.5±2.1 g C kg^{-1} soil (5 year plot), 33.4±1.7 g C kg^{-1} soil (45 year plot) and 30.2±1.8 g C kg^{-1} soil (75 year plot). However, in the soil of the fallow land and of the 45 year old agricultural plot, the significant ($p<0.01$) differences in SOM content resulted in insignificant changes in the total amount of WSA. Only the 75 year agricultural management, compared to the fallow land, led to a significant decline of SOM content ($p<0.01$) and total amount of WSA ($p=0.05$) in the soil. If the treatments of fallow land, 45 and 75 year agricultural management were considered together, positive correlation of the total amount of WSA was stronger with clay ($R=0.78$, $p=0.01$) than with SOM content ($R=0.62$, $p=0.07$) in the whole soil samples. These results supported the findings of Denef and Six (2005) who reported that SOM played a lesser role than clay in the formation and stabilization of WSA in heavy-textured soils. Nevertheless, in the clayey loam Haplic Chernozem the SOM content of ~30 g C kg^{-1} soil can be considered as a threshold (critical) value at which the unfavourable and significant decline in water-stable aggregation was observed.

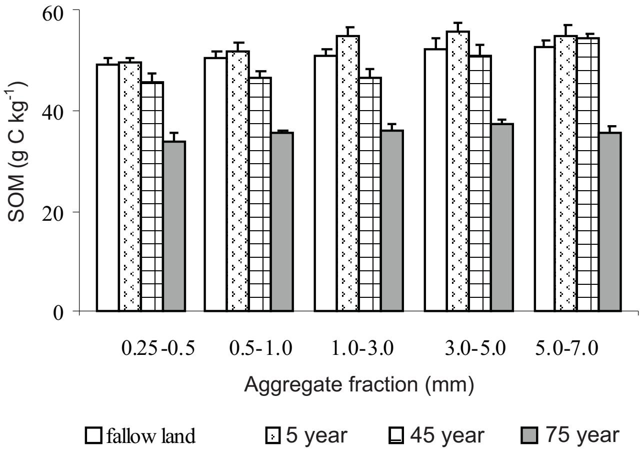

Fig. 2. Soil organic matter content (SOM, g C kg^{-1}) in water-stable aggregate size fractions of a clayey loam Haplic Chernozem on plots with fallow land and 5, 45, and 75 year agricultural management. Vertical bars are standard deviations (at $p \leq 0.05$ and $n=3$).

The SOM content in the separate size fractions of WSA was significantly ($p=0.01$) higher than that in the whole soil samples (Fig. 2).

These results showed that SOM was more protected against microbial mineralization in WSA than in the non-aggregated portion of the soil. However, sequestration of SOM in the WSA size fractions was less pronounced in all the agricultural treatments than in the fallow land. Among the agricultural treatments, significantly ($p<0.001$) the lowest SOM content was found in all the WSA size fractions of soil of the 75 year old agricultural plot, probably being a result of clay loss from this soil (Cheshire *et al*., 2000). There were also significant ($p<0.05$) differences of SOM content in the WSA size fractions of 0.25-0.5 to 1.0-3.0 mm in the fallow land and the 45 year old agricultural plot. If all four treatments were combined together, SOM content in WSA showed strong positive correlations with the amount of WSA fractions of 1.0-3.0 mm ($R=0.86$, $p<0.001$), 3.0-5.0 mm ($R=0.72$, $p=0.01$), and 5.0-7.0 mm ($R=0.81$, $p=0.001$).

Both BR and MBC play an important role in the formation and stabilization of WSA. Our results also showed that soil microbial properties were becoming significantly ($p<0.05$ to $p<0.001$) worse with increasing duration of soil agricultural use. For instance, BR of the whole soil samples reached 23.4±0.4 mg CO_2-C kg^{-1} soil h^{-1} on the fallow land, 16.6± 0.4 mg CO_2-C kg^{-1} soil h^{-1} on the 5 year plot, 15.8±0.2 mg CO_2-C kg^{-1} soil h^{-1} on the 45 year plot, and 10.9±0.4 mg CO_2-C kg^{-1} soil h^{-1} on the 75 year plot. Whereas, the microbial biomass carbon content in the whole soil samples of the same plots was 480.0±67.6, 371.2±10.2, 370.1±5.4, and

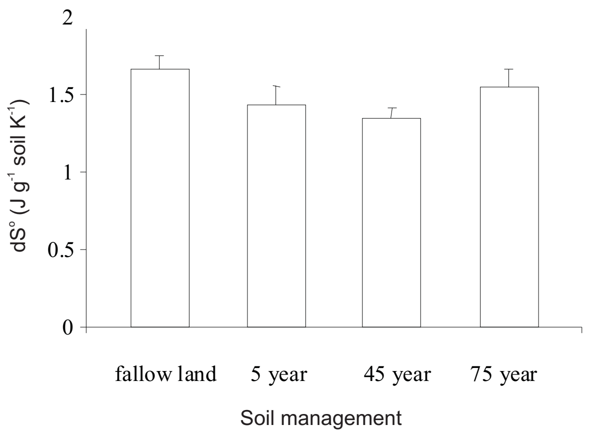

Fig. 3. Differential entropy of water vapour adsorption (dS°, J g^{-1} soil K^{-1}), in a clayey loam Haplic Chernozem on plots with fallow land and 5, 45 and 75 year agricultural management. Vertical bars are standard deviations (at $p \leq 0.05$ and n=3).

340.2± 5.9 mg C kg^{-1} soil, respectively. The total amount of WSA had stronger positive correlation with BR (R=0.65, p<0.05) than with MBC content (R=0.40).

The above-mentioned findings on the management-induced changes in the total amount of SOM, clay and WSA of the soil were also supported by our data on the differential entropy of water vapour adsorption. Curves for the relationships between differential entropy of water vapour adsorption and moisture content of an adsorbent are known to reach a minimum at covering adsorbent surface with a complete monolayer of molecules in close-packed array. The lowest values of differential entropy of water vapour adsorption on the energetically active surface of adsorbent reflect the establishment of the most stable thermodynamic equilibrium in the system.

Among the studied treatments, the lowest values of differential entropy of water vapour adsorption were observed in the whole soil samples from the 45 year old agricultural plot (Fig. 3). Removal of hydrophobic organic substances from the surface of clay minerals (montmorillonite) could lead to the appearance of high energy centres with great affinity to water vapour adsorption by solid phase of this soil (Józefaciuk and Bowanko, 2002; Sokołowska *et al*., 1993).

Mainly the 75 year management-induced losses of clay particles could lead to the formation of adsorption centres with low energy and, as a result, to an increase of minimum values of differential entropy of water vapour adsorption by this soil (Gerasimov *et al.*, 1969; Sokołowska and Józefaciuk, 2004). Therefore, the thermodynamic state of the soil solid phase in this treatment might be less stable than that in the 45 and 5 year agricultural treatments. These results gave a wider view on the already studied subject (Józefaciuk *et al*., 2001; Józefaciuk and Bowanko, 2002; Raytchev *et al*., 2005), providing information about the effects of short- and long-term agricultural soil use on the thermodynamic characteristics of clayey loam Haplic Chernozem. These data also supported the above-mentioned conclusion that clay minerals played a leading role in maintaining favourable physical state of the heavy-textured soil under the long-term agricultural management.

CONCLUSIONS

1. The only 75 year agricultural management of the clayey loam Haplic Chernozem resulted in a significantly decrease in content of clay, water-stable aggregates, soil organic matter and microbial biomass carbon.

2. From the point of view of soil resilience and quality, a threshold (critical time) of continuous agricultural management of this soil is equal to 75 years.

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