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ORIGINAL PAPER

DYNAMICS OF ORGANIC MATTER IN SOILS FOLLOWING A CHANGE IN LANDUSE ON PERMO-CARBONIFEROUS ROCKS IN THE ČESKÝ BROD AREA (CZECH REPUBLIC)

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ABSTRACT

Organic matter properties of soils were studied in a territory covered by Stagnosols after afforestation. We quantified the impact of afforestation on the amount and distribution of free organic matter, microaggregates (unstable and stable under low-intensity sonification) and their components in the upper horizons of former arable soils overgrown by different species of forest vegetation. The duration of 45 years after afforestation was revealed to be not sufficient for a complete renewal of soil humus state, which appears only after till 115 years of the duration of forest cenosis. The carbon storage in light fractions remains lower by 21–40 % relative to that of forest soil, including significant losses of free organic matter (42–58 %) and occluded organic matter (12–33 %), which present the most active part of soil organic matter. The positive impact of the deposit regime, expressed by a sharp improvement of the carbon cycle balance, is reflected by the $C_{unstable}/C_{stable}$ ratio, which decreases from 6.2 in arable soil to 2.4 on average in forest stands.

INTRODUCTION

Afforestation of agricultural soils is an important tool for improving the landscape structure and its ecological stability. This trend was reflected in the composition of soil cover of the Czech Republic in the last fifty years. The area of arable soils has decreased from 3351570 ha to 2965606 ha and the area of forest soils has increased from 2599628 ha to 2669850 ha (Český úřad zeměměřický a katastrální, 2017).

Studies about the influence of change in landuse on soils in the Czech Republic usually involve data about aggregate stability, biological characteristics, chemical properties and soil structure. Such information can be found in the studies of Podrázský and Ulbrichová (2004), Holubík et al. (2014), Vacek et al. (2016) and Artemyeva et al. (2017).

Soil carbon dynamics during afforestation is very important due to its role in terrestrial ecosystem carbon balance and the global carbon cycle. Evaluation of soil organic carbon based on various chemical, physical and physicochemical analyses has been made by Podrázský et al. (2009, 2015), Korkanç (2014), and Szoboszlay et al. (2017). The method of granulo-densimetric fractionation allows isolation of functionally important soil organic matter components, which are relatively homogeneous with regard to morphological features, chemical composition, and resistance to mineralization. This approach of evaluate of organic carbon was published in the papers of Artemyeva et al. (2009, 2013), Kalinina et al. (2013, 2015), Popelau and Don (2013), Artemyeva and Kogut (2016) and Li et al. (2016). The distribution of organic matter on this basis has not been described yet from soils of the Czech Republic.

The aim of this study is to characterize the dynamics of the different organic matter pools in upper horizons of soils following a change in landuse.

MATERIAL AND METHODS

The research area lies in the Blanice Graben which is a major fault system 200 km long, trending NNE–SSW. This basin has been preserved in a discontinuous series of relics of which the most important are the Český Brod relic in the north and the České Budějovice relic in the south. The Blanice Graben is filled with Permo-Carbononiferous sand- and clay-dominated sediments with red coloration deposited at 305 to 300 Ma. Holub (2001) distinguished four units within the sedimentary fill: the Peklov and Lhotice Members of the Černý Kostelec Formation and the Chýnov and Bulánka Members of the Český Brod Formation. The studied locality lies in the Chýnov Member which consists of sandstones and arkoses. The characteristic rock of the

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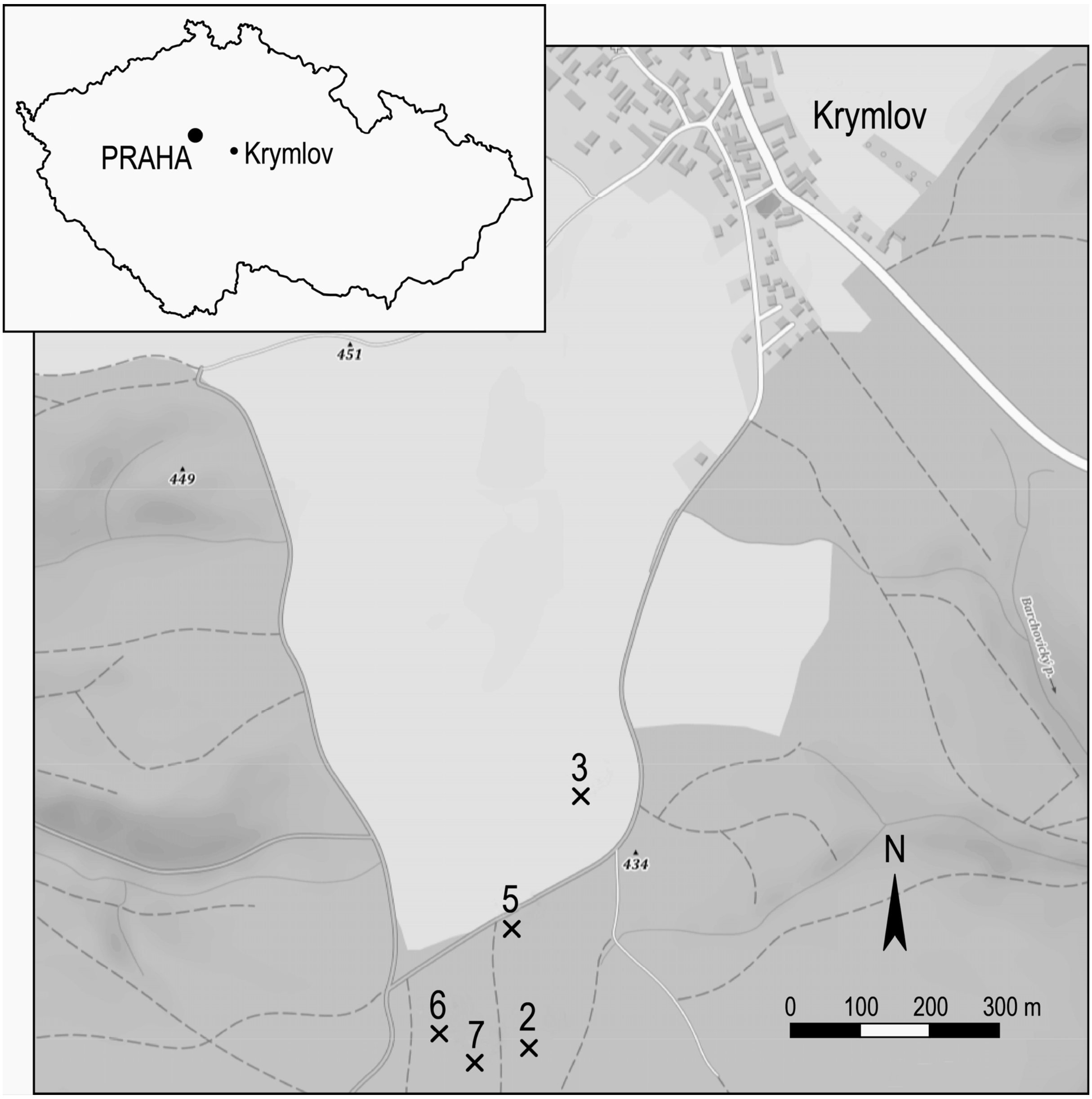

Fig. 1 Localization of the soil profiles.

studied area is arkose. It consists of monocrystalline and polycrystalline quartz, K-feldspar, plagioclase and a small amount of clay minerals.

The study sites lie approximately 45 km southeast of Prague (Fig. 1). Selection of soil profiles was guided by a soil survey. The soils were described in the field according to Jahn et al. (2006). Individual soil profiles are classified according to IUSS Working Group WRB (2015) as Stagnosols. Data including coordinates, vegetation and landuse are shown in Table 1.

The area of Krymlov 2 is a forest 115 year in age with 50 % Scots pine (*Pinus sylvestris L.*) and 50 % Norway spruce (*Picea abies*). The site of Krymlov 3 represents arable soil with oilseed rape (*Brassica napus*). The research was also conducted at sites with a different type of forest: 45 years in age, established on former agricultural lands. These sites were afforested by white birch (*Betula alba* – Krymlov 5), Scots pine (*Pinus sylvestris L.* – Krymlov 6) and Douglas fir (*Pseudotsuga menziesii* – Krymlov 7).

Basic chemical properties such as $pH_{H2O,}$ pH_{KCl} and cation exchange capacity were discussed by Artemyeva et al. (2017). These data are summarized in Table 2.

Physical properties of soils except O horizons were determined in undisturbed core samples 100 cm^3 in volume. Steel cylinders of this volume were pressed into the soil and measured using the standard method (Dane and Topp, 2002).

Different methods are currently applied to study carbon distribution in various organic matter pools (Blanco-Canqui and Lal, 2004). The results obtained depend on the method selected (Ashamn et al., 2003). We used a modified variant of granulo-densimetric fractionation (Artemyeva and Kogut, 2016). This scheme allows subdividing soil microaggregates into four groups according to their stability to sonification,

Table 1 Basic information about the studied sites.

Locality	Coordinate N	Coordinate E	Vegetation	Landuse
Krymlov 2	49°56'40.1"	14°55'32.6"	50 % Norvay spruce + 50 % Scots pine	Forestry 115 years in age
Krymlov 3	49°56'47.7"	14°55'30.4"	Oilseed rape	Crop agriculture
Krymlov 5	49°56'43.6"	14°55'30.3"	White birch	Forestry 45 years in age
Krymlov 6	49°56'40.9"	14°55'28.9"	Scots pine	Forestry 45 years in age
Krymlov 7	49°56'39.7"	14°55'30.9"	Douglas fir	Forestry 45 years in age

Table 2 Chemical and physical properties.

Locality	Horizon	Depth	pH_{H2O}*	pH_{KCl}*	CEC*	BD	PD	P
		cm			mM.100 g^{-1}	g.cm^{-3}	g.cm^{-3}	%
Krymlov 2	Ahg	0-14	3.75	3.16	13.54	1.36	2.48	45.30
	Bg1	14-65	4.43	3.38	16.40	1.71	2.41	29.05
	Bg2	65-88	4.65	3.43	8.11	1.82	2.40	24.17
	Cg	88-117	4.92	3.56	15.23	1.89	2.42	21.90
Krymlov 3	Apg	0-18	5.60	4.84	16.90	1.34	2.42	44.84
	AhgBg1	18-31	5.94	5.05	11.75	1.56	2.40	35.63
	Bg1	31-85	4.78	3.64	14.29	1.69	2.36	28.39
	Bg2	85-110	4.90	3.53	18.99	1.72	2.41	28.43
	Cg	110-130	5.05	3.41	17.16	1.75	2.36	25.85
Krymlov 5	Ahg	0-11	4.61	3.83	11.06	1.35	2.34	42.16
	AhgBg1	11-22	4.53	3.79	10.17	1.37	2.37	42.05
	Bg1	22-50	4.61	3.63	16.01	1.58	2.33	32.04
	Bg2	50-90	4.57	3.53	14.85	1.84	2.32	22.47
	Cg	90-114	4.62	3.55	11.91	1.97	2.32	15.08
Krymlov 6	Ahg	0-19	4.05	3.49	11.42	1.43	2.36	39.27
	Bg1	19-59	4.67	3.65	13.50	1.65	2.34	29.63
	Bg2	59-101	4.72	3.62	17.32	1.71	2.27	24.52
	Cg	101-125	4.85	3.66	15.76	1.96	2.32	15.51
Krymlov 7	Ahg	0-18	4.41	3.68	10.98	1.38	2.36	41.66
	Bg1	18-39	4.48	3.52	10.56	1.51	2.36	36.16
	Bg2	39-60	4.24	3.38	16.57	1.76	2.32	24.13
	Cg	60-80	4.32	3.36	14.18	1.80	2.37	24.05

*The results were adopted from Artemyeva et al. (2017), CEC – cation exchange capacity, BD – bulk density, PD – particle density, P – porosity

and the properties of organic and organo-mineral components: nonoccluded (free) organic matter (LF_{fr}), occluded organic matter (LF_{ooc} = LF_{ooc1} + LF_{ooc2}), organo-clay complexes (Clay), and residue (Res) see Figure 2. According to the microaggregate stability concept (Edwards and Bremner, 1967), the soil components identified over short term (5–15 min.) ultrasonic processing are constituents of coarse (unstable) microaggregates of 50–250 µm in size. Other soil components are constituents of fine (stable) microaggregates, 1–50 µm in size.

The soil fractionation scheme is presented in Figure 2. Before granulo-densimetric fractionation soil samples were air-dried and passed through a 1 mm sieve. A probe-type ultrasonic vibrator (LUZD-0,5K-02-00000 PS Criamid, Russia) was used for physical dispersion of soils. After a sonication (75 J.ml^{-1}) of the soil sample (10 g + 50 ml deionized water) for 1 min. and centrifugation of the aqueous suspension of soils according to the Stokes Law (the procedure was repeated 15 times), the aqueous-clay suspension was collected and dried (80 °C). The clay fraction (Clay) was removed from the soil sample, and the light fractions (densities of 2.0 and 1.8 g.cm^{-3}) were isolated according to a simplified scheme by extraction with a bromoform-ethanol mixture (BEM). Fractions with a density of <1.8 g.cm^{-3} were sieved into two subfractions: light fractions containing particles >50 µm – nonoccluded organic matter, localized in the interaggregate space (LF_{fr}), and finer particles (<50 µm) localized within microaggregates (LF_{ooc}). The scheme was described in detail by Artemyeva and Kogut (2016). All separations were performed in two replicates.

Coarse microaggregates with a diameter of 50–250 µm are unstable under sonification and consist of variably humified organic residues (LF_{occ} = LF_{occ1} + LF_{occ2}) and organo-clay complexes (Clay). The connection between the components is loose, and they are readily disconnected under sonification.

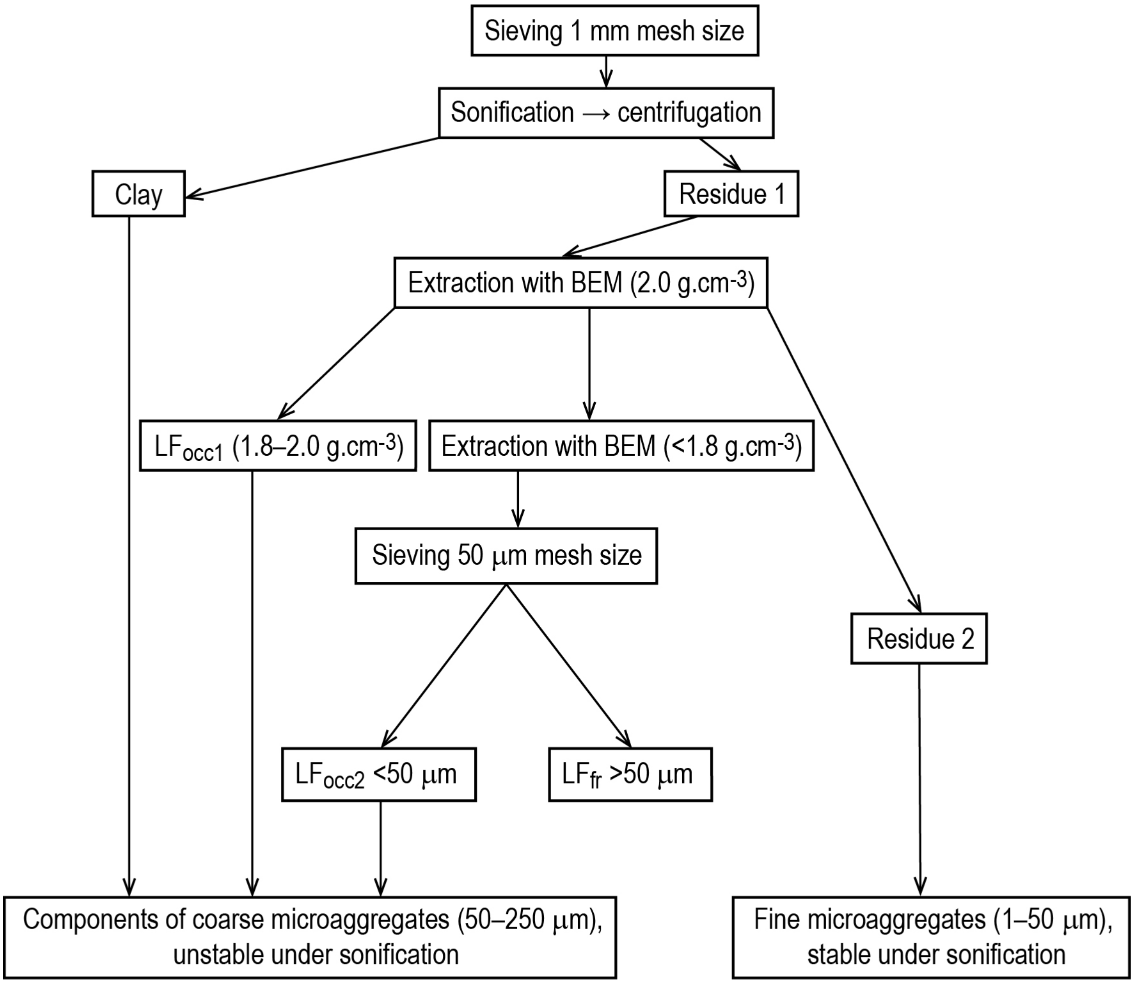

Fig. 2 Soil fractionation scheme (adopted and modified from Artemyeva and Kogut, 2016).
BEM – bromoform-ethanol mixture, LF_{occ1} – occluded organic matter (light fraction with density 1.8-2.0 g.cm^{-3}), LF_{occ2} – occluded organic matter (light fraction with density <1.8 g.cm^{-3} and a size <50 µm), LF_{fr} – free organic matter (light fraction with density <1.8 g.cm^{-3} and a size >50 µm)

Fine microaggregates with a diameter of 1–50 µm, stable under sonification (Residue), also consist of clay particles and organic matter but the connection between the components is very strong and they do not disconnect under sonification.

The carbon content in the soil and fractions was determined in duplicate using the combustion catalytic oxidation method – TOC Analyzer (Shimadzu, Japan).

The statistical data processing was carried out using the Statistics Package. The selected significance level was $\alpha = 0.05$.

RESULTS AND DISCUSSION

PHYSICAL PROPERTIES

Physical properties are summarized in Table 2. The value of bulk density increases in the direction to the parent material. This tendency was observed at all sites. Bulk densities of Apg and Ahg horizons are practically the same after 45 years of change in landuse. In contrast, Korkanç (2014) described decreasing values of bulk density in the upper part of soil profiles developed on marble after black pine and cedar afforestation. Different results are probably connected with different conditions of pedogenesis. Stagnosols are at least temporarily influenced by surface water, mainly rainfall. They show periodically reducing conditions resulting in stagnic properties. Soils developed on marble are classified according to the IUSS Working Group WRB (2015) as Leptosols. These soils are characterized by wetting through precipitation only, with no additional wetting. Water percolates through the soil profile freely without any prolonged retention on the impermeable horizon.

Particle density characterized the solid phase of soils. The measured values correspond to the type of parent material and also, in the case of Apg and Ahg horizons, to the content of organic matter.

Porosity was calculated from the bulk and particle density. The distribution of porosity in soil profiles has opposite tendency than bulk density. These results were obtained in all soil profiles. Porosity of the Ahg horizon, except of Krymlov 2, decreased by 2.68 % to 5.57 % 45 years after afforestation.

The analysed samples revealed differences in the physical properties of upper part of soil profiles after a change in landuse. Stagnosols of forest stands established on agricultural lands demonstrated the

Table 3 Bulk of organic and organo-clay fractions (%).

Locality	Horizon	Depth cm	LF_{fr}	LF_{occ2}	LF_{occ1}	Clay	Residue
Krymlov 2	Ahg	0-14	0.39±0.12	0.75±0.24	0.55±0.14	11.91±0.22	86.40±0.47
Krymlov 3	Apg	0-18	0.16±0.10	0.73±0.10	0.79±0.16	11.23±0.14	87.09±0.49
	AhgBg1	18-31	0.19±0.10	0.66±0.08	0.82±0.14	11.73±0.21	86.60±0.52
Krymlov 5	Ahg	0-11	0.21±0.08	0.63±0.27	0.65±0.16	11.16±0.27	87.34±0.78
	AhgBg1	11-22	0.16±0.06	0.34±0.06	0.53±0.10	12.04±0.31	86.93±0.53
Krymlov 6	Ahg	0-19	0.18±0.10	0.54±0.12	0.69±0.10	10.44±0.31	88.15±0.61
Krymlov 7	Ahg	0-18	0.18±0.10	0.44±0.06	0.55±0.12	10.74±0.21	88.09±0.46

LF_{fr} – free organic matter (light fraction with density <1.8 $g.cm^{-3}$ and a size >50 μm), LF_{occ2} – occluded organic matter with density <1.8 $g.cm^{-3}$ and a size <50 μm, LF_{occ1} – occluded organic matter with density 1.8-2.0 $g.cm^{-3}$

same value of bulk density and predominantly slightly decreasing value of porosity.

PROPERTIES AND DISTRIBUTION OF ORGANIC AND ORGANO-CLAY FRACTIONS

These data are presented in Table 3. The bulk of light fractions (LF) under ploughing remains practically unchanged. In all the studied former arable soils overgrown by different species of forest vegetation, LF bulk decreases in the order: white birch (-11.3 %) <pine (-16.1 %) <Douglas fir (-30.4 %), relative to arable soil.

Studies of accumulation level and distribution of different LF subfractions showed more obvious differences between the studied soils. The abundance of free organic matter (LF_{fr}), is more than 2.4 times higher in forest soil, relative to arable soil. Forest cenosis, unlike herbaceous, is characterized by high productivity and reserves of decomposed organic material (Bazilevich et al., 1986) and less favourable climate conditions for microbial activity in forest soils, as compared to arable soils. This determines the high level of accumulation of free organic matter, which is presented, substantially, by readily degradable and visually well discernible fragments of vegetation. In all studied forest stands the bulk of free organic matter (LF_{fr}) increases in the order: Scots pine and Douglas fir (+12.5 %) <white birch (+31.2 %), relative to the arable soil, which is due to the absence of alienation of fresh organic matter with the harvest, contributing to its accumulation in the soil.

Occluded organic matter (LF_{occ2}), defined as that with particle density of <1.8 $g.cm^{-3}$ and size of <50 μm, differs from that of larger size (>50 μm) by their morphological and chemical characteristics. This fraction is enriched by aromatic components and depleted in carbohydrates, which, apparently, is associated with higher degree of humification of plant material (Golchin at el., 1994; Artemyeva and Fedotov, 2013). The abundance of this subfraction (LF_{occ2}) in the arable horizon decreases only by 2.7 % relative to forest soil. In all studied forest stands the bulk of this fraction decreases in order as: white birch (-13.7 %) <Scots pine (-26 %) <Douglas fir (-39.7 %), relative to arable soil.

We observed sharp increase of the accumulation level of another occluded organic matter fraction (LF_{occ1}), defined as that with particle density of <1.8–2.0 $g.cm^{-3}$, under ploughing. This fraction is enriched by siliceous compounds of biogenic origin (Golchin et al., 1994; Artemyeva and Fedotov, 2013). This is due to a large quantity of cereals in agrocenosis, compared to forest cenosis. It is known that phytoliths are amorphous silica microbiomorphs. They form in plants, especially in cereals during their vital functioning (Golyeva, 2001). Afforestation causes the reduction of this fraction bulk in the upper horizons of forest stands from 13 to 30 %, relative to arable soil.

THE DISTRIBUTION OF CARBON IN THE Apg AND Ahg HORIZONS

The total carbon contents (C_t) in the upper horizons of the studied soils vary from 1.2 to 1.7 % (Table 4). Ploughing causes a decrease in carbon storage in the arable horizon: 1.46 % (Krymlov 2) against 1.20 % (Krymlov 3). Afforestation provokes an increase in C_t up to 1.3–1.7 %, relative to arable soil.

After the withdrawal of soil from agricultural use, processes promoting differentiation of the former arable horizon by carbon content develop in soil under the canopy of white birch forest. This has been noted by many researches (Litvinovich et al., 2004; Litvinovich and Pavlova, 2007; Smal and Olszewska, 2008; Kalinina et al., 2013). First of all, it is attributed to processes of profile renewal, which is typical for the given biocenosis. In the case of several humus horizons in a soil profile (Krymlov 5), the C_t difference between the upper and lower humus horizons may reach the factor of 1.2 (Table 4).

Taking into account the different number and thickness of humus horizons in the studied soils, it seems appropriate to analyse the total carbon storage and carbon accumulated in different organic and organo-mineral fractions in the upper 10 cm layer, taking into consideration the bulk density (Table 5).

It has been demonstrated that intensive ploughing may significantly disturb the balance of humification and mineralization processes, due to the activation of meso- and microbiological activity,

Table 4 Carbon in organic and organo-mineral fractions (% in soil).

Locality	Horizon	Depth cm	LF_{fr}	LF_{occ2}	LF_{occ1}	Σ_{LF}	Clay	Residue	C_t
Krymlov 2	Ahg	0-14	0.12±0.04	0.21±0.10	0.06±0.02	0.39±0.08	0.67±0.03	0.40±0.07	1.46±0.08
Krymlov 3	Apg	0-18	0.05±0.02	0.24±0.10	0.06±0.02	0.35±0.14	0.69±0.04	0.16±0.03	1.20±0.15
	AhgBg1	18-31	0.06±0.02	0.21±0.08	0.06±0.02	0.33±0.12	0.68±0.05	0.32±0.05	1.33±0.01
Krymlov 5	Ahg	0-11	0.07±0.02	0.19±0.06	0.05±0.02	0.31±0.10	0.78±0.02	0.36±0.03	1.45±0.15
	AhgBg1	11-22	0.05±0.02	0.09±0.04	0.03±0.02	0.17±0.08	0.60±0.05	0.49±0.07	1.26±0.05
Krymlov 6	Ahg	0-19	0.05±0.01	0.16±0.02	0.04±0.02	0.25±0.05	0.71±0.03	0.73±0.06	1.69±0.01
Krymlov 7	Ahg	0-18	0.05±0.02	0.15±0.02	0.03±0.02	0.23±0.06	0.75±0.03	0.31±0.07	1.29±0.06

LF_{fr} – free organic matter (light fraction with density <1.8 g.cm^{-3} and a size >50 μm), LF_{occ2} – occluded organic matter (light fraction with density <1.8 g.cm^{-3} and a size <50 μm), LF_{occ1} – occluded organic matter with density 1.8-2.0 g.cm^{-3}, Σ_{LF} – light fraction with density <2.0 g.cm^{-3}, C_t – total carbon

resulting in the improvement of water, air and soil thermal regimes. This process is aggravated by the lower content of fresh organic matter in the soil due to the alienation of fresh organic matter with the harvest and, as a result, provokes significant acceleration of the organic matter mineralization. The intensity of these negative processes may be reduced by the application of agricultural technologies and, above all, by organic fertilizers. For example, the losses of carbon in the studied forest soils under ploughing in the upper 10 cm layer are 19 % of the initial value, which is almost 1.5 times lower relative to those of Albeluvisols from the centre of the Russian plain (Artemyeva, 2010), cultivated with the application of much lower doses of organic fertilizers (~1 t.ha^{-1}). Apparently, this is due to the application of agricultural technologies and particularly organic fertilizers in the form of crushed and ploughed straw in the dry contents of grain 6 t.ha^{-1} or rape 3 t.ha^{-1} and the N mineral fertilization (Artemyeva et al., 2017).

Data analysis clearly revealed a trend of increase of carbon storages in the upper mineral horizons (layer thickness 10 cm) of forest stands, which is in compliance with literature data (Leifeld and Kogel-Knabner, 2005; Christensen, 1992; Guggenberger and Zech, 1999). The C_t storage increases from 16.1 to 17.8–19.6 t.ha^{-1}, not reaching, however, the level of natural forest soil biocenosis (19.9 t.ha^{-1}). An exception was observed only for the soil developing under the canopy of a Scots pine forest (Krymlov 6), where the carbon accumulation was even higher than that of a Scots pine forest and Norway spruce forest (Krymlov 2): 24.2 t.ha^{-1} versus 19.9 t.ha^{-1}, respectively (an increase by almost 22 %). This is due to the cessation of cultivation of forest soils and development of a secondary forest in their place. The total carbon storages in the studied soils at forest stands after withdrawal from agricultural use form a succession: Douglas fir (+10.7 %) <white birch forest (+21.7 %) <Scots pine (+ 50.3 %), relative to arable soil.

One of the important processes that determine the state of organic matter in arable soils is the mineralization of discrete organic matter (LF). The carbon storages of light fractions in the upper 10 cm layer of arable soil are lower by almost 12 % relative to that of forest soils: 4.7 versus 5.3 t.ha^{-1}, respectively. After a withdrawal of arable soil from agricultural use, the carbon storage of discrete organic matter sharply decreases in the order: Douglas fir (-32.4 %) <Scots pine (-23.9 %) <white birch (-10.9 %) relative to arable Stagnosol (22.4 % ± 12.2, on average – Table 5).

The most significant changes in the studied soil occur with free organic matter (LF_{fr}). Ploughing provokes a sharp decline of the carbon storages of free organic matter ($C_{LF}{}^{fr}$ in the upper 10 cm layer of Krymlov 3) by almost 59 % from the initial values, relative to forest soil. The carbon storages in soils of forest stands form a succession: Douglas fir (+3 %) <Scots pine (+6 %) <white birch (+42 %), relative to arable soil, due to the absence of alienation of fresh organic matter with the harvest (Table 5).

The application of organic fertilizers is able to decrease the degree of mineralization processes intensity. In effect, we observed an increase in carbon storages of occluded organic matter (LF_{occ2}) by almost 12 % relative to that of forest soil (Krymlov 2 – Table 5). Apparently, organic fertilizers with different degrees of fermentation are the substances attractive enough to the microbial community of agricultural soil, and are immediately colonized and included into the unstable to sonification microparticles. After a withdrawal of arable soil from agricultural use, the carbon storage of this fraction decreases in the order: Douglas fir (-35.7 %) >Scots pine (-28.9 %) >white birch (-20.5 %) relative to arable soil (28.4 % ± 8.6 on average).

On the contrary, for another fraction of occluded organic matter (C_{LFocc1}) ploughing causes only a slight decrease in the carbon storage (less than 2.4 % relative to forest soil). Later, after the withdrawal of arable soil from agricultural use, the value of carbon storage in all studied soils of secondary forest decreases in the order: Douglas fir (-48.7 %) >Scots pine (-28.7 %) >white birch (-16.3 %) compared to arable soil (31.2 % ± 18.5 on average – Table 5). This is due to a sharp decline in the quantity of cereal

Table 5 Carbon storages of organic and organo-mineral fractions in 10 cm layer of Ahg and Apg horizons (t.ha^{-1}).

Locality	Horizon	LF_{fr}	LF_{occ2}	LF_{occ1}	Σ_{LF}	Clay	Residue	C_t
Krymlov 2	Ahg	1.6±0.5	2.9±1.3	0.8±0.3	5.3±1.1	9.1±0.5	5.4±0.5	19.9±8.9
Krymlov 3	Apg	0.7±0.3	3.2±1.3	0.8±0.3	4.7±1.9	9.2±0.6	2.1±0.3	16.1±4.7
Krymlov 5	Ahg	1.0±0.4	2.6±0.8	0.7±0.3	4.2±1.4	10.5±0.3	4.9±0.3	19.6±2.0
Krymlov 6	Ahg	0.7±0.2	2.3±0.3	0.6±0.3	3.6±0.7	10.2±0.4	10.4±0.9	24.2±0.2
Krymlov 7	Ahg	0.7±0.3	2.1±0.3	0.4±0.3	3.2±0.9	10.4±0.4	4.3±0.5	17.8±7.7

LF_{fr} – free organic matter (light fraction with density <1.8 g.cm^{-3} and a size >50 μm), LF_{occ2} – occluded organic matter (light fraction with density <1.8 g.cm^{-3} and a size <50 μm), LF_{occ1} – occluded organic matter with density 1.8-2.0 g.cm^{-3}, Σ_{LF} – light fraction with density <2.0 g.cm^{-3}, C_t – total carbon

vegetation, which forms amorphous silica microbiomorphs during the vital functioning, as a result of removal agrocenosis.

The carbon storages of organo-clay complexes in the upper 10 cm layer under ploughing increases very slightly (9.1 versus 9.2 t.ha^{-1}, respectively) and by only 1.5 % relative to forest soil (Table 5). The carbon storages of organo-clay complexes in soils of forest stands increase in the order: Scots pine (+9.7 %) <Douglas fir (+11.9 %) <white birch (+13.8 %) relative to arable soil (11.8 % ±2.3 on average).

The carbon storages of Residue in the upper 10 cm layer under ploughing are sharply reduced from 5.4 to 2.1 t.ha^{-1} (-60.7 % relative to forest soil) see Table 5. After a withdrawal of arable soil from agricultural use, carbon storages in soils of secondary forests show steady increases in the order: Douglas fir (+100 %) <white birch (+127 %) <Scots pine (+388 %) relative to arable soil (205 % ± 180 on average), without reaching, however, the value in forest soil of 115 years in age (5.44 t.ha^{-1}). An exception was observed only for the soil under the canopy of a Scots pine forest, where the carbon storages of Residue were higher than the value at Krymlov 2 (almost doubled). Taking into consideration that microparticles resistant to ultrasonic treatment are present in this fraction, we can conclude about a steady increase in the order Douglas fir (-32.4 %) <Scots pine (-23.9 %) <white birch (-10.9 %) relative to arable Stagnosol (22.4 % ± 12.2 on average) see Table 5.

The most significant changes in the studied soil occur with free organic matter (LF_{fr}). Ploughing provokes a sharp decline of the carbon storages of free organic matter (C_{LF}^{fr} in the upper 10 cm layer of Krymlov 3) by almost 59 % from the initial values, relative to forest soil. The carbon storages in soils of forest stands form a succession: Douglas fir (+3 %) < Scots pine (+6 %) <white birch (+42 %), relative to arable soil, due to the absence of alienation of fresh organic matter with the harvest (Table 5).

The application of organic fertilizers is able to decrease the degree of mineralization processes intensity. In effect, we observed an increase in carbon storages of occluded organic matter (LF_{occ2}) by almost 12 % relative to that of forest soil (Krymlov 2), see Table 5. Apparently, organic fertilizers with different degrees of fermentation are the substances attractive enough to the microbial community of agricultural soil, and are immediately colonized and included into the unstable to sonification microparticles. After a withdrawal of arable soil from agricultural use, the carbon storage of this fraction decreases in the order: Douglas fir (-35.7 %) >Scots pine (-28.9 %) >white birch (-20.5 %) relative to arable soil (28.4 %±8.6 on average).

On the contrary, for another fraction of occluded organic matter (C_{LFocc1}) ploughing causes only a slight decrease in the carbon storage (less than 2.4 % relative to forest soil). Later, after the withdrawal of arable soil from agricultural use, the value of carbon storage in all studied soils of secondary forest decreases in the order: Douglas fir (-48.7 %) >Scots pine (-28.7 %) >white birch (-16.3 %) compared to arable soil (31.2%±18.5 on average) see Table 5. This is due to a sharp decline in the quantity of cereal vegetation, which forms amorphous trend of improving the conditions for the formation of stable microparticles in the soil after withdrawal from the agricultural use and, consequently, an increase in sustainable organic matter in soil (Artemyeva, 2010; Artemyeva and Fedotov, 2013; Artemyeva and Kogut, 2016). A similar trend of increasing organic content of stable aggregates <20 μm in size was observed in a study on soil organic matter by changing landuse patterns in Bavaria (Leifeld and Kogel-Knabner, 2005).

Data analysis revealed qualitative differences in the composition of light fraction in the upper layer of the studied soils. In forest soil (Krymlov 2), almost 31 % of carbon is represented by free organic matter (LF_{fr}), whereas in the arable layer the share of this fraction is less than 15 % of C_{LF} (Table 6). In soils of forest stands, the share of free organic matter increases to 20–23 % of the C_{LF}, without reaching, however, the initial level of forest soil for a specified period of time (45 years).

The share of occluded organic matter (LF_{occ2}) in the forest soil is slightly over a half – almost 54 % – of the C_{LF}. Ploughing provokes a sharp increase in the proportion of this fraction – up to 68.6 % of the C_{LF}. In soils of forest stands the share decreases to 61–65 % of C_{LF}, without reaching, however, the initial level of forest soil (Krymlov 2) for a specified period of time (45 years) see Table 6. The share of another fraction – occluded organic matter (C_{LFocc1}) – is very

Table 6 The composition of light fractions in 10 cm layer of Ahg and Apg horizons (% of C_{LF}).

Locality	Horizon	LF_{fr}	LF_{occ2}	LF_{occ1}
Krymlov 2	Ahg	30.7±15.9	53.9±14.1	15.4±1.7
Krymlov 3	Apg	14.2±0.4	68.7±0.9	17.1±1.3
Krymlov 5	Ahg	22.7±1.1	61.2±2.2	16.0±1.1
Krymlov 6	Ahg	19.9±0.2	64.1±4.9	16.0±4.7
Krymlov 7	Ahg	21.8±4.2	65.3±9.0	12.9±4.8

C_{LF} – carbon storage in light fraction with density <2.0 g.cm^{-3}, LF_{fr} – free organic matter (light fraction with density <1.8 g.cm^{-3} and a size >50 µm), LF_{occ1} – occluded organic matter with density 1.8-2.0 g.cm^{-3}, LF_{occ2} – occluded organic matter (light fraction with density <1.8 g.cm^{-3}and a size <50 µm)

Table 7 The distribution of carbon in organic and organo-clay fractions in 10 cm layer of Ahg and Apg horizons (% of C_t).

Locality	Vegetation	C_{LF}^{fr}	C_{LF}^{occ}	C_{clay}	C_{res}
Krymlov 2	50 % Norvay spruce + 50 % Scots pine	8.2	18.5	45.9	27.4
Krymlov 3	Oilseed rape	4.2	25.0	57.5	13.3
Krymlov 5	White birch	4.9	16.5	53.8	24.8
Krymlov 6	Scots pine	2.9	11.8	42.0	43.2
Krymlov 7	Douglas fir	6.9	13.9	58.1	24.0

C_t – total carbon, C_{LF}^{fr} – carbon storage in free organic matter, C_{LF}^{occ} – carbon storage in occluded organic matter, C_{clay} – carbon storage in organo-clay fraction, C_{res} – carbon storage in Residue

low: it represents just over 15 % of the C_{LF} in the forest soil. Ploughing causes an increase in the proportion of this fraction: almost to 17.1 % of C_{LF}, which is, apparently, due to the considerably higher quantity of cereals in the agrocenosis, compared to the forest. In soils of forest stands the proportion decreases to intermediate value (~ 16 % of C_{LF}), reflecting the still large quantity of cereals in the studied soils of forest cenosis (Table 6). An exception was observed only for the Douglas fir forest soil (Krymlov 7), where a very low share of this fraction was revealed (13 % of C_{LF}). Apparently, this is due to a lower projective coverage of the soil of the grassland ecological community.

In the upper 10 cm layer of Krymlov 2, the discrete organic matter (LF) represents ~ 27 % of C_t (Table 7). Ploughing causes a slight increase in the proportion of discrete organic matter – up to 29 % of C_t. Overgrowth of former arable soil by different species of forest vegetation provokes a decline of the discrete part of organic matter in soil carbon and forms a succession: white birch <Douglas fir <Scots pine (Table 7).

The analysis of the share of organo-clay complexes in C_t revealed that ploughing causes a significant increase: from 46 to 58 % of C_t (Table 7). This is primarily due to the impact of heavy agricultural machinery, which disrupts the natural soil structure. Overgrowth of former arable soil by different species of forest vegetation reduces these negative effects, so the share of organo-clay complexes in C_t decreases in the order: white birch (-4 %) <Scots pine (-16 %) relative to arable soil. An exception was observed only for the soil under the canopy of the Douglas fir (Krymlov 7), where a slight increase in the share of organo-clay complexes of + ~1 % was revealed relative to arable soil.

Thus, the main bulk of carbon in the studied soils is represented by light fractions (LF) and organo-clay complexes (Clay). The quantity of these main fractions in the studied soils varies, mainly lying within the limits of 57–87 % of C_t (Table 7).

The share of carbon accumulated by Residue in C_t of forest soil is 27 % of C_t. The share of this fraction decreases under ploughing – up to 13 % of C_t (more than doubled), primarily due to the impact of heavy agricultural machinery, which disrupts the natural soil structure and contributes to the destruction of microparticles stable (under low-intensity sonification) under conditions of a native cenosis. After a withdrawal of arable soil from agricultural use and overgrowth by different species of forest vegetation, the share of this fraction sharply and steadily increases (+11 ÷ 30 % from initial value) in the order: Douglas fir (+11 %) <white birch (+12 %) <Scots pine (+30 %) relative to arable soil. This reflects the improvement of conditions for the formation of stable microparticles and the resulting accumulation of sustainable organic matter in soil (Table 7).

Along with the processes of mineralization of organic matter under ploughing, the disaggregation process develops. As a result, the composition of soil microstructure components altered. In soils where structural stabilization is controlled by organic matter, a direct link can be seen between organic decomposition and the dynamics of soil aggregation. Carbon storage of components of unstable (to ultrasonic treatment) microparticles largely depends on the intensity of dehumification and disaggregation processes. Carbon accumulation occurs due to 1. The acceleration of mineralization intensity of LF due to improvement of ecological conditions for micro-organisms, 2. low inputs of fresh organic matter and 3. reduction of stable microparticles strength. The study of the distribution of carbon share of organic and organo-clay fractions in the upper 10 cm layer of Ahg horizons of Stagnosols studied in terms of their location in the soil matrix revealed that the microstructural organization of soil is significantly affected by the landuse. So, ploughing dramatically increases the share of carbon accumulated in the unstable (to ultrasonic treatment) microparticles (+18 % of C_t relative to the initial value), the components of which are represented by LF_{occ} (LF_{occ1} + LF_{occ2}) and organo-clay complexes. Accordingly, the share of Residue (the most sustainable soil organic matter) decreases by 13 %. This is accompanied by a sharp increase in the $C_{unstable}/C_{stable}$ ratio, which is 2.4 in soils of the forest cenosis and 6.2 in soils of the agrocenosis.

The overgrowth of former arable soil by different species of forest vegetation provokes a significant reduction in the share of carbon accumulated in the unstable (to ultrasonic treatment) microparticles, forming the succession: Douglas fir (-11 %) < white birch (-12 %) < Scots pine (-29 %) relative to arable soil. This is followed, as has been already noted above, by a sharp increase in the share of Residue and a decrease in the $C_{unstable}/C_{stable}$ ratio down to 1.3–3.0.

CONCLUSION

The study was performed in the territory covered by Stagnosols developed on arkoses. The applied method of granulo-densimetric fractionation indicates that the soils withdrawn from agricultural production demonstrate qualitative and quantitative changes of humus state. Pedogenesis of the studied Stagnosol is governed by identical factors of soil formation, with the exception of biological factor, which is different. The process of overgrowth of former arable soil by vegetation considerably changes the main factor of accumulation of organic matter in the soil – the vegetation, which provides an intensive renewal of fresh organic material. Gradual replacement of the biogeocenosis over time should lead to the accumulation of dead biomass that promotes an increase in the content of light fractions, which are the most sensitive to changes in environmental conditions pool of soil organic matter.

The sharp reduction in the accumulation of discrete organic matter in soils of forest stands relative to arable soil is, apparently, due to a complex of factors including lithological characteristics of the soils. These factors together with the lack of projective coverage of the soil are not able to provide the necessary conditions for the fixation of the newly formed organic matter by soil mineral matrix and organic matter is thus quickly mineralized. Thus, the given environmental conditions and the considered time interval (45 years) are not sufficient for a renewal of the soil humus state to the initial level before tillage.

At the same time, it should be noted that the significant increase in the carbon accumulation level in Residue in the upper 10 cm layer from 2.1 $t.ha^{-1}$ (arable soil) to 4.3–10.4 $t.ha^{-1}$ (forest stands) and the increase in the proportion from 13 % to 24–43 % of C_t (i.e., by the factor of 2–5), respectively, show a significant improvement in the conditions for the formation of stable microparticles. This improvement is favourably reflected in the balance of humification and mineralization processes in the studied soils as soon as 45 years after the withdrawal from agricultural production. This is confirmed by the increase in the $C_{unstable}/C_{stable}$ ratio, which is used as an index of the equilibrium of the carbon cycle and soil stability: the value decreases from 6.2 in arable soil to 1.3–3.0 (2.4±1.0) in forest stands (Artemyeva, 2010, Artemyeva and Kogut, 2016). So, significant fluctuations in the value of $C_{unstable}/C_{stable}$ in Stagnosol after withdrawal from agricultural use show variable degrees of environmental sustainability of the soils of forest stands, which are probably at different stages of their development.

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