https://doi.org/10.17221/174/2018-SWR

Impact of different fallow durations on soil aggregate structure and humus status parameters

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Citation: Burdukovskii M., Kiseleva I., Perepelkina P., Kosheleva Y. (2019): Impact of different fallow durations on soil aggregate structure and humus status parameters. Soil & Water Res.

Abstract: Soil aggregate structure and soil organic matter are closely interrelated and commonly considered as key indicators of soil quality. The aim of this study was to evaluate the effects of different fallow durations on indices of soil structure and humus status indicators. Studies were conducted on abandoned agricultural fields (15, 20 and, 35 years after abandonment). As a reference site, we used a cultivated field in the area. The experimental soil fields are classified as Gleyic Cambisols. Soil macroaggregates were separated with the sieve (dry sieve) to seven aggregate size fractions, i.e.> 10, 10–5, 5–2, 2–1, 1–0.5, 0.5–0.25 and < 0.25 mm. The humus status parameters of soils included the following indicators: soil organic carbon (C_{org}), humus reserves (Q_H), the degree of humification of organic matter (SOM_{dh}), fractions of humic acids (HA) (free and bound with monovalent cations and Al_2O_3, Fe_2O_3, bound with Ca^{2+} which forms humates, bound with clay minerals), fulvic acids (FA) (free aggressive) and ratio of HA to FA ($C_{HA}:C_{FA}$). After a fallow period of more than 20 years on the surface formation of a sod layer. A long-term fallow period had an impact on the mean weight diameter of the aggregates (MWD) and agronomically valuable aggregates (AVA). Fallow soils have a significantly better structure than soils under a cultivated field. Long-term cultivation leads to the deterioration of soil structure and the formation of large aggregates (>10 mm). The C_{org} content remains at the level of the background content when the soils are left fallow for less than 15 years and increases over time. The C_{org} in the upper 0–20 cm soil layer has been shown to increase from 3.55 to 8.74% on arable land that has been fallow for 35 years and has been largely associated with significant accumulation of organic matter within the plant root mass. Mature sites are characterized by an increase of fulvic acids in the humus composition in comparison with their arable analogues. The abandonment of soil agricultural use and the cessation of mechanical tillage results in the restoration of the natural structure of soils and the improvement of their agrophysical properties. Such studies have not been previously conducted in the Primorsky region of the Russian Far East.

Keywords: dry-sieved macroaggregates; fallow land; soil quality; soil structure

The aggregate structure of soils and soil organic matter (SOM) are closely interrelated and commonly considered as key indicators of soil quality (Bronick & Lal 2005; Liao *et al.* 2006; Dexter *et. al.* 2008; Wiesmeier *et al.* 2012). Soil organic matter is a complex system and composed of organic compounds, differing in mechanisms of their fixation in the soil and in their functions in carbon cycling and soil formation (Bronick & Lal 2005; Bin & Xin-Hua 2006). Literature data about changes in soil carbon stocks due to land use changes are frequently discussed in review articles (Post & Kwon 2000; Guo & Gif-

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Supported by the Russian Science Foundation, Project No. 17-76-10011.

https://doi.org/10.17221/174/2018-SWR

ford 2002; Laganiere *et al.* 2010). The results of numerous studies have enabled the characterisation of changes in the composition of SOM as a result of ploughing forest soils (Gajic *et al.* 2010; Ciric *et al.* 2012). However, data referring to changes in the composition of SOM with the transition from arable land into forest are still scarce. The cessation of anthropogenic impact on soils (soil cultivation, harvest, fertiliser use, etc.) as well as successional changes in vegetation lead not only to carbon stock changes but also to changes in the composition of SOM. According to some sources, the soil organic carbon (C_{org}) content of cultivated soil decreases with agricultural use (Bronick & Lal 2005; Litvinovich & Pavlova 2007; Ciric *et al.* 2012). Other sources have indicated that the fractions of fulvic acids increase in overgrowing arable land while the proportion of humic acids decreases (Chalaya 2012).

The aggregate structure of soils also undergoes significant changes during revegetation, both because of the inherent characteristics of the soil and the influence of natural biocoenoses formed in fallow soils (Baeva *et al.* 2017). The aggregate structure of soils is usually expressed as the degree of aggregate stability in water (Tisdall & Oades 1982). Numerous studies have been conducted on the effects of land use change on aggregate stability, but notably less attention has been devoted to dry aggregate size distribution and the factors affecting it (Elliot 1986; Ciric *et al.* 2012). However, aggregate size distribution is one of the major physical characteristics of soil and strongly affects soil fertility and its resistance to erosion and degradation (Shein 2005; Gajic *et al.* 2010; Laganiere *et al.* 2010; Wiesmeier *et al.* 2012). Soil aggregation conserves and protects SOM, which functions as a plant nutrient and energy reservoir (Bronick & Lal 2005; Liao *et al.* 2006), and usually deteriorates together with C_{org} (Ciric *et al.* 2012). The soil structure affects a wide range of soil properties, including soil porosity, compactability and water retention (Regelink *et al.* 2015; Cheng *et al.* 2015).

At the same time, many factors affect the postagrogenic dynamics of soil properties during revegetation. The abandonment of soil agricultural use leads to improved aggregate stability since it reduces physical disruption and contributes to the organic matter accumulation, especially in the upper horizons (Gajic *et al.* 2010; Baeva *et al.* 2017).

Land withdrawal from the fallow state to arable land is becoming a worldwide trend and also significant in Russia (Lyuri *et al.* 2010). The issues of fallow soil transformation with a return to agricultural use in the Far-Eastern region of Russia remain poorly studied, as there are practically no studies concerning the changes in the level of fertility and basic soil properties. We hypothesised that the soil quality is higher in long-term fallow soils compared to croplands subjected to long-term, intensive tilling. In this context, the objective of this study is to evaluate the effects of different fallow durations on indices of soil structure and humus status indicators.

MATERIAL AND METHODS

Studies were conducted from July to September 2017 on the former arable land in the Primorsky region of the Russian Far East (Table 1). These fields were abandoned in different years. Site age after abandonment was 15, 20 and 35 years. Soil samples were also selected from a reference site (unfertilised) of a long-term field experiment which started in 1941 on the territory of the Primorsky Scientific Research Institute of Agriculture of the Russian Academy of Sciences. This field was cultivated with soybean.

The experimental soil fields are classified as Gleyic Cambisols according to IUSS Working Group WBR (2006). These are the soils which cover the largest proportion in the Primorsky region and are intensively used in agriculture (more than 50% of the cropland) (Ivanov 1976; Burdukovskii *et al.* 2016).

Gleyic Cambisol soils are characterised by the clayey texture (the content of clay and silt particles

Table 1. Description of the studied sites

Fallow ages (years)	Geographic coordinates		Soil type	Vegetation type
	latitude N	longitude E		
0	43.859 189	131.945 269	Gleyic Cambisols	soybean
15	43.837 730	132.093 442	Gleyic Cambisols	graminoids/sagebrush
20	43.751 206	132.020 417	Gleyic Cambisols	graminoids/sagebrush/grasses
35	43.842 654	131.917 306	Gleyic Cambisols	sedges/graminoids

0 – ploughland (a cultivated field)

https://doi.org/10.17221/174/2018-SWR

in the top horizon is 80–85%), and the bulk density varied from 0.82 to 1.22 g/cm^3 in the plow layer and 1.09–1.05 in the subsoil. These parameters specify the low water permeability of the soils. The soils were slightly acidic, with levels of pH (H_2O) and pH (KCl) ranging from 5.46 to 6.12 and from 4.48 to 5.12, respectively.

The climate of the study area is influenced by the monsoon. In January, north, north-west, and west winds dominate whereas, in July, the winds are from the south, south-east, and east. The winter climate is arid and frosty, with an average air temperature in January −13°C and a humidity of 26 to 48%. The summer monsoon climate is cloudy and rainy with an average air temperature in August of 19°C and a humidity of less than 80%. Most precipitation occurs from August to September when the typhoons bring in significant rains. The hydrology is characterised by desiccation in spring and humidification in summer and at the beginning of autumn (Timofeeva *et al.* 2014).

Soil samples were taken randomly at different locations within the same plot, in triplicate. The soil pits were dug by hand. The soils were sampled from the humus-accumulative horizons at 0–20 and 20–30 cm depth. After a fallow period of more than 20 years, the arable horizon had divided into subhorizons with differing morphological properties, so we selected samples at 0–12 and 12–30 cm depths. All samples from the same layer within each plot were carefully mixed to obtain a composite sample and air-dried at room temperature.

Aggregate soil analysis was performed via dry sieving of mixed samples. We obtained seven aggregate size fractions, i.e.> 10, 10–5, 5–2, 2–1, 1–0.5, 0.5–0 and < 0.25 mm. The weight of these fractions we used for the determination of mean weight diameter (MWD) (Hillel 2004), structure coefficient (K_s) and agronomically valuable aggregates (AVA) (Shein 2005).

The content of C_{org} was determined using the Tyurin method. The fractional composition of humus was determined according to the Tyurin method as modified by Ponomareva and Plotnikova, humus reserves (Q_H) in the 0–20-cm layer and the degree of humification of organic matter (SOM_{dh}) was determined by Orlov *et al.* (1981). The humus status parameters of soils (C_{org}, Q_H, SOM_{dh}), humic acids (HA) (free and bound with monovalent cations and Al_2O_3, Fe_2O_3, bound with Ca^{2+} which forms humates, bound with clay minerals), fulvic acids (FA) (free aggressive) and ratio of HA to FA ($C_{HA}:C_{FA}$) were characterised according to Orlov *et al.* (2004).

The data were analysed using the software packages Microsoft Excel and SPSS software (Ver. 22, 2013). Relationships between soil structure indices and humus status indicators were estimated using the mean values, standard errors, analysis of variance (two-way ANOVA) and Pearson's correlation coefficients; significant differences between treatments were determined at $P \leq 0.05$ and $P \leq 0.01$.

RESULTS AND DISCUSSIONS

The cessation of anthropogenic impacts and the colonisation of former agricultural soils by natural vegetation leads to changes in the structural organisation. The nature and direction of such post-agricultural transformation, along with the soil development history and initial soil properties, significantly depends on biological factors. For example, the root system of herbaceous plants penetrates the soil and loosens the soil mass, thereby creating aggregates of a certain shape (Tisdall & Oades 1982). In addition, the products of organic matter decomposition serve as glue, binding microaggregates into macroaggregates (Elliot 1986).

According to various authors (Gajic *et al.* 2010; Ciric *et al.* 2012), Cambisols have an increased content of non-desirable large aggregates (> 5 mm). An analysis of the aggregate structure of former arable soils has shown that the content of macroaggregates in the surface layer > 5 mm decreases in the following order (Figure 1): ploughland (39%) > fallow soil 15 years (20%) > fallow soil 20 years (6%) > fallow soil 35 years (1–2%). In general, 1–5-mm fractions predominate in the aggregate structure of Gleyic Cambisols.

The ratio of small and large macroaggregates changes in the course of secondary succession. Thus, the proportion of soil aggregates with a size of 2–0.25 mm increases over time (from 27.57% in ploughland to 63.28% in 35-year-old fallow soil). After a fallow period of more than 20 years, soils show morphological changes in the arable horizon. This was especially evident in the 35-year-old site, in which the loose sod layer was clearly visible on the soil surface (Litvinovich *et al.* 2009). A lack of macroaggregates with a size > 10 mm and a high level (27%) of aggregates < 0.25 mm compared to the other sites was observed in the first layer (0–12 cm) of the 35-year-old site.

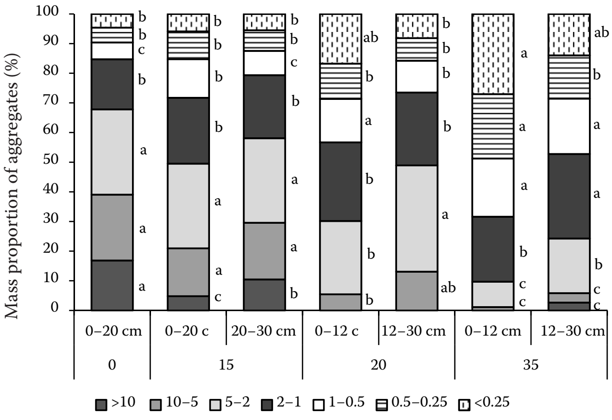

Figure 1. Soil aggregate size fractions distribution in fallow soils of different ages

The numbers 15, 20 and 35 indicate years after abandonment; 0 – ploughland (a cultivated field); different lowercase letters indicate significant differences at $P < 0.05$

The highest content of aggregates with a size > 10 mm was noted in the ploughed field (16.8%), probably because the root system of herbaceous plants promotes better loosening of the soil mass in the course of succession compared with the annual physical disturbance of the soil structure during cultivation (Ciric *et al.* 2012; Wiesmeier *et al.* 2012).

Agronomically valuable aggregates with a size of 10 to 0.25 mm determine the structure of the soil. Lumpy aggregates (> 10 mm) and dusty aggregates (< 0.25 mm) are undesirable and may adversely affect the agrophysical properties of the soil (Shein 2005). The optimum aggregate structure in soils of loamy and clay granulometric composition is formed with an AVA content of 70–80%. In the upper horizon of the studied soils, AVAs accounted for more than 70%, which indicates their excellent aggregate state (Figure 2). The AVA content in the former arable horizon of the 15-year-old fallow soils was 10% higher compared to that of the cultivated soil. Similar results were also obtained by Gajic *et al.* (2010) and Baeva *et al.* (2017) who found that the content of the AVA in long term arable soil is lower than in fallow and forests soils.

Soil structure is an important and characteristic feature in determining the agro-production characteristics of soils. It is considered favourable if K_s ranges between 0.67 and 1.50 and unfavourable at $K_s < 0.67$ (Shein 2005). The observed soil structure in fallow and arable soils of the current use stage is rated as favourable ($K_s > 1.50$). The highest K_s value was found for the 15-year-old fallow site (8.37). In more mature soils, K_s values are lower, probably as a result of stratification of the arable horizon and the formation of a sod layer on the surface. The distribution of aggregate size by fractions is complex and difficult to describe by a single mathematical dependence; it is, therefore, common to use the MWD index. Our results showed that MWD was clearly dependent on the age of the fallow period and tillage management, and the most significant effect on reducing the diameter of the aggregates was for soil that had been fallow for 35 years (Figure 2). As a result of compaction by agricultural machinery with long term tillage, the soil has more large aggregates (>10 mm) (Wiesmeier *et al.* 2012). Soils under native vegetation have a substantially higher amount of AVA compared to croplands. Mean weight diameter of the aggregates in the former arable layer of the 20-year-old site (1.84 mm) was 2.5 times less

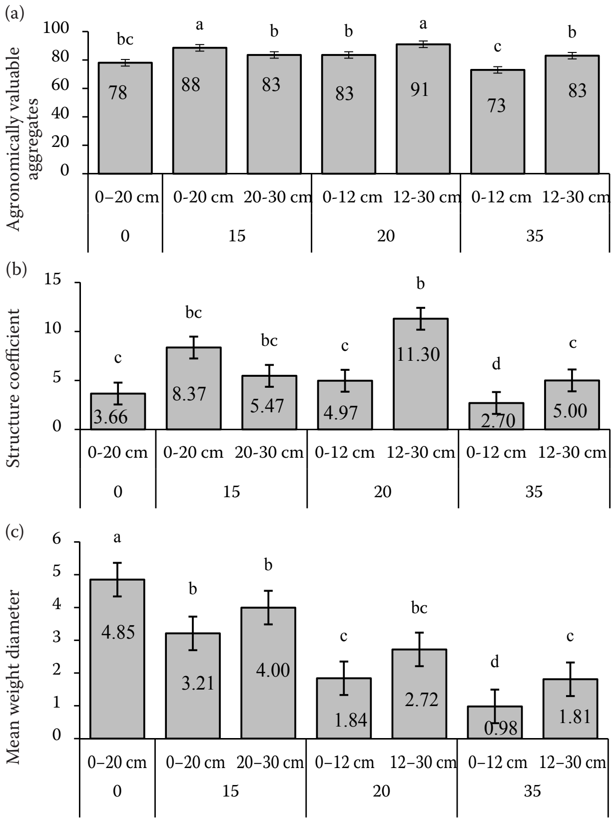

Figure 2. Effects of the fallow period on (a) agronomically valuable aggregates (%); (b) structure coefficient and (c) mean weight diameter (mm)

The numbers 15, 20 and 35 indicate years after abandonment; 0 – ploughland (a cultivated field); vertical bars in each column indicate standard error of the mean; different lowercase letters indicate significant differences at $P < 0.05$

https://doi.org/10.17221/174/2018-SWR

Table 2. Correlation coefficients between soil structure indices and humus status indicators

	Size fractions in mm (mass %)							MWD (mm)	AVA (%)
	> 10	10–5	5–2	2–1	1–0.5	0.5–0.25	> 0.25		
> 10	ns	0.891**	0.915**	0.893**	0.764*	ns	ns	0.764*	ns
10–5	ns	ns	0.823**	0.979**	ns	ns	ns	0.823*	ns
5–2	ns	ns	ns	0.854**	ns	ns	ns	0.816*	ns
2–1	ns	ns	ns	ns	0.806*	ns	ns	0.639*	ns
1–0.5	ns	ns	ns	ns	ns	ns	ns	ns	ns
0.5–0.25	ns	ns	ns	ns	ns	ns	0.894**	ns	0.977**
>0.25	ns	ns	ns	ns	ns	ns	ns	ns	0.852**
C_{org}	–0.632*	–0.724*	–0.791*	–0.564*	ns	ns	ns	–0.968**	ns
Q_H	ns	ns	ns	ns	ns	ns	ns	ns	ns
C_{HA1}	ns	ns	ns	ns	ns	ns	ns	ns	ns
C_{HA2}	ns	ns	ns	ns	ns	–0.872*	–0.83	ns	ns

MWD – mean weight diameter; AVA – agronomically valuable aggregates; C_{org} – soil organic carbon; Q_H – humus reserves; C_{HA1} – HA free and bound with monovalent cations and Al_2O_3, Fe_2O_3; C_{HA2} – HA bound with Ca^{2+} which forms humates; **P* ≤ 0.05%; ***P* ≤ 0.01%; ns – not significant

than that in the cultivate site (4.85 mm). This may be because the systematic ploughing involves the involvement and redistribution of the soil from the underlying horizons to the arable one. This soil mass can be well structured but is less resistant to mechanical tillage (Bronick & Lal 2005; Ciric *et al.* 2012). Evidence suggests that The abandonment of soil agricultural use and the cessation of mechanical tillage use results in the restoration of their natural structure and the improvement of agrophysical properties, as has been confirmed by other researchers (Post & Kwon 2000; Litvinovich *et.al.* 2009; Gajic *et al.* 2010; Cheng *et al.* 2015; Baeva *et al.* 2017). We found no significant correlation between humus characteristics and soil structure parameters; however, we observed positive correlations between fraction sizes and MWD (Table 2). A highly significant correlation ($P < 0.01$) between the aggregate fractions < 5 mm and AVA was observed, and close correlations ($P < 0.05$) between aggregate fractions > 1 mm and MWD. Our results are consistent with data from other researchers (Ciric *et al.* 2012.

A division of the arable horizon into subhorizons, both in terms of morphological properties and organic matter, was observed for soils which had been abandoned for more than 20 years. Based on evaluative indicators (Orlov *et al.* 2004), the C_{org} content in the abandoned sites was low and below average.

The high C_{org} content in the 35-year-old fallow soil compared to the other sites (Table 3) was largely associated with significant accumulation of organic matter with the plant root mass. The upper part of the former arable horizon was transformed into the

Table 3. Changes in the humus status parameters in fallow soils of different ages (tested soil depth 0–20 cm)

Fallow ages (years)	C_{org} (%)	Q_H (t/ha)	C_{HA1}	C_{HA2}	C_{HA3}	SOM_{dh}	C_{FA1a}	$C_{HA}:C_{FA}$
			(%)					
0	3.55 ± 0.14^a	115.52 ± 9.57^b	24.34 ± 1.05^a	64.33 ± 4.12^c	11.32 ± 0.74^b	34.52 ± 2.37^a	3.27 ± 0.23^b	1.74 ± 0.02^a
15	3.36 ± 0.03^a	62.07 ± 6.09^a	34.17 ± 2.11^b	32.47 ± 2.34^b	30.42 ± 2.97^a	31.61 ± 2.25^a	5.33 ± 0.21^c	0.95 ± 0.07^b
20	5.53 ± 0.10^b	122.46 ± 8.75^b	34.12 ± 2.66^a	33.14 ± 2.18^b	32.78 ± 2.24^a	38.27 ± 3.09^b	4.64 ± 0.66^a	1.35 ± 0.09^a
35	8.74 ± 0.22^c	102.92 ± 7.33^b	56.11 ± 1.28^c	12.12 ± 1.14^a	31.43 ± 3.26^a	32.83 ± 2.48^a	4.36 ± 0.43^a	0.97 ± 0.03^b

C_{org} – soil organic carbon; Q_H – humus reserves; SOM_{dh} – degree of humification of organic matter; C_{HA1} – HA free and bound with monovalent cations and Al_2O_3, Fe_2O_3; C_{HA2} – HA bound with Ca^{2+} which forms humates; C_{HA3} – HA bound with clay minerals; C_{FA1a} – fulvic acids free aggressive; C_{HA}/C_{FA} – proportions of humic acids and fulvic acids; 15, 20 and 35 indicate years after abandonment; 0 – ploughland (a cultivated field); values are means ($n = 3$), with standard error; different letters within each column indicate significant differences in soils ($P < 0.05$)

sod layer, which was most distinct in the mature sites under sedge-graminoid vegetation. The upper horizon on these fields was densely penetrated by intertwined living and dead plant roots. The formation of a sod layer on the surface also affected soil temperature and water content, which in turn affected the rate of decomposition of plant residues and the soil organic matter (Litvinovich *et al.* 2007; Wright *et al.* 2007; Yu *et al.* 2015).

According to various previous studies (Havkina 2004; Purtova *et al.* 2016), the humus contents in the study site vary from 3.30 to 4.30% in arable soils. Based on these data, the humus content in the soil remains at the level of the background content when the soils are left fallow for less than 15 years. An increase in the C_{org} content was observed in more mature fallow soils. In addition, based on archive data for defined fields (archival materials of agrochemical surveys, Federal Scientific Center of the East Asia Terrestrial Biodiversity FEB RAS), the humus content increased in the course of secondary succession (from 3.72 to 5.53% in the 20-year-old site), probably as a result of organic matter accumulation, which confirmed the results of Liao *et al.* (2006), Bin and Xin-Hua (2006), Wright *et al.* (2007).

The QH in the 0–20-cm layer the 15-year-old fallow Gleyic Cambisol were characterised as low (62.07 t/ha), while in more mature soils, they were average. The SOM_{dh}, i.e. the amount of humus substances in the SOM, of all abandoned soils was relatively high.

The contents of C_{HA1} (brown humic acids) and C_{HA2} (grey humic acids) were almost in equal proportions. The proportion of brown humic acids of the total content of humic acids was mostly low (34.12–36.81%) and, in rare cases, mean (56.11%). The proportion of grey humic acids of the total content of humic acids was very low and low (12.12–33.57%) in all examined soils.

The $C_{HA} : C_{FA}$ ratio has been used as an index of the degree of humification (Stevenson 1994). Arable soils are characterised by humic type of humus ($C_{HA} : C_{FA} = 1.74$). Fallow soil humus had a humate-fulvate composition and fulvate-humate composition. In our opinion, this was due to the water-air regime of Gleyic Cambisols. This soil is subject to surface overwetting, whereby the organic matter transformation process is somewhat decelerated, and the preservation and slowing down of humification of plant residues occurs (Wolf & Snyder 2003; Havkina 2004).

Grey humic acids predominate in the humus composition of arable soils in the study area, accounting for more than 60% of the total content of humic acids (Havkina 2004), which is a characteristic feature of well-cultivated soils saturated with exchangeable bases. Site abandonment results in negative changes in the fraction-group composition of humus. We also observed a reduction in the proportion of C_{HA2} bound to Ca^{2+} in abandoned sites, probably as a result of the cessation of mineral and organic fertiliser application (Litvinovich & Pavlova 2007; Lapa *et al.* 2011). Mature sites are characterised by an increase of fulvic acids in the humus composition, which can be easily observed in their $C_{HA} : C_{FA}$ ratios in comparison with their arable analogues. The proportion of C_{HA3} bound to clay minerals was high in all examined soils, while the proportion of C_{FA1}a of total C_{org} was mainly low and, in rare cases, mean (5.33%).

CONCLUSIONS

The abandonment of soil agricultural use and the cessation of mechanical tillage results in the restoration of the natural structure of soils and the improvement of their agrophysical properties. Fallow soils have a significantly better structure than soils under a cultivated field. The humus content of the Gleyic Cambisols remained at the level of the background content in sites abandoned for less than 15 years and increased over time when the arable horizon was divided into subhorizons both in terms of morphological properties SOM. Long-term cultivation leads to the deterioration of soil structure and the formation of large aggregates (> 10 mm). After a fallow period of more than 20 years, a significant decrease in MWD and a small increase in AVA was observed. The SOM_{dh}, i.e. the amount of humus substances in the SOM, was generally high in all abandoned sites. The humus had a humate-fulvate composition and, albeit less often, a fulvate-humate composition. In the abandoned sites, a reduction in the proportion of C_{HA2} bound to Ca^{2+} in comparison with their arable analogues was noted. The value of these findings is highly significant because no such studies have been conducted before in the Primorsky region of the Russian Far East.

Acknowledgements. The analyses described in this work were performed using equipment from the Instrumental Centre for Biotechnology and Gene Engineering at the Federal Scientific Center of the East Asia Terrestrial Biodiversity FEB RAS.

https://doi.org/10.17221/174/2018-SWR

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Received for publication September 3, 2018
Accepted after corrections April 22, 2019