Scientific Papers. Series A. Agronomy, Vol. LXVII, No. 1, 2024
ISSN 2285-5785; ISSN CD-ROM 2285-5793; ISSN Online 2285-5807; ISSN-L 2285-5785

SOIL CARBON SEQUESTRATION AND STOCKS FOLLOWING LAND-USE TYPES CHANGE

Angela KUTOVA[1], Larysa SHEDIEI[1], Ievgen SKRYLNIK[1], Volodymyr MYKHAYLYN[2], Ivan SEMENENKO[2]

[1]NSC «Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky», 4 Chaykovska Street, 61024, Kharkiv, Ukraine
[2]Institute of Vegetables and Melons Growing, 1 Institutska Street, 62478, Selektsiine village, Kharkiv District, Kharkiv Region, Ukraine

Corresponding author email: orgminlab@gmail.com

Abstract

The influence of agricultural activities on virgin soils leads to the loss of organic carbon, which leads to degradation processes in the soil ecosystem. This paper on the example of a Typical Chernozem, the content and stock of organic carbon in virgin soils (fallow, mottled virgin soil, absolute virgin soil) and arable soil was studied. Study was conducted in long-term field experiments with the cultivation of vegetable and grain agricultural crops and on the territory of the «Mykhailivska Tsilyna» conservation in Forest-Steppe zone of Ukraine. We was discuss the main factors influencing soil carbon sequestration following land-use change. It has been established that there is a stabilization level of carbon content for each type of land use, and approximate levels of absorption by the soil, which are possible under management, have been calculated.

***Key words**: soil organic carbon, land use types, application of fertilizers, stocks of soil carbon.*

INTRODUCTION

Soil is the largest terrestrial pool of organic carbon. Small changes in the soil organic carbon (SOC) stock could result in significant impacts on the atmospheric carbon concentration. The fluxes of SOC vary in response to a host of anthropogenic and environmental factors. Scientists worldwide are contemplating questions such as: "What is the average net change in soil organic carbon due to environmental conditions or management practices?", "How can soil organic carbon sequestration be enhanced to achieve some mitigation of atmospheric carbon dioxide?" and "Will this secure soil quality?" (Stockmann et al., 2013).

Sequestration of atmospheric carbon in soils through improved management of agricultural land is considered to have high potential for global CO_2 mitigation. However, the potential of soils to sequester SOC in a stable form, which is limited by the stabilization of SOC against microbial mineralization, is largely unknown (Wiesmeier et al., 2014).

The scientific literature on various aspects of carbon storage in soils has given rise to the introduction of several terms when discussing the amounts of carbon that are, or could be, stored in soils. The term «carbon sequestration potential», in particular, is used with different meanings, sometimes referring to what might be possible given a certain set of management conditions with little regard to soil factors which fundamentally determine carbon storage (Ingram & Fernandes, 2001).

The term «Attainablemax» is defined and is suggested as the preferred term for carbon sequestration in mineral soils, being more relevant to management than «potential» and thereby of greater practical value.

Soil carbon sequestration implies transferring of atmospheric CO_2 into soil of a land unit through its plants. Threshold level of SOC in the root zone is 1.5-2.0% (Lal et al., 2015). To 1-m depth, more than 50% total carbon pool is contained between 0.3 and 1 m depth. According to other scientists (Gamaley et al., 2010; Virto et al., 2012; Stockmann et al., 2013), losses and accumulation of organic matter and SOC occur mainly in 0.2-0.4 m depth of soil.

Human activities have degraded soils worldwide, causing a gap between soil carbon capacity and current storage. Restoring carbon in agricultural soils particularly is seen as a win-win climate solution, since management practices that would restore soil carbon can improve soil health, reduce chemical fertilizer needs, while also providing a effective solution to combat climate change (Lal et al., 2015; Bossio et al., 2020).

Was find that soils with high carbon content are characterized by substantial adsorption of carbon compounds onto mineral soil per unit of soil carbon and vice versa for soils with low carbon content (Doetterl et al., 2015).

Precipitation and temperature were only secondary predictors for carbon storage, respiration, residence time and stabilization mechanisms.

Studies of land use change gave the first indications of the differences between particulate organic matter (POM) and mineral associated organic matter (MAOM) in the context of change. Early studies showed POM to be more vulnerable to loss upon cultivation (Cambardella & Elliott, 1992), this concept was deemphasized as attention grew around physical protection in aggregates, and the roles of different aggregate size classes as soil organic matter (SOM) diagnostic features (Plaza-Bonilla et al., 2014; Six et al., 2000).

Changes in SOC and aggregate stability as a result of agricultural practices is site and crop specific. Mbanjwa et al. (2022) study, SOC and aggregate stability were evaluated under undisturbed grassland, cultivated pasture and arable land uses from the 0-5, 5-10 and 10-20 cm depths. In all soils, SOC was significantly lower under arable cultivation (range from 1.4 to 2.1%) compared to the grassland and pasture (3.4 to 4.2%) in the top 10 cm. The soil carbon stocks followed a similar trend to the SOC in all soils and under all land uses. The loss of SOC and decline in aggregate stability over a period of 38 years of continuous arable cultivation in the near surface layers of two of the soils are potentially problematic for soil sustainability in the longer term.

Has been recognized that the adsorption of organics to clay and silt particles is an important determinant of the stability of organic matter in soils. Hassink's hypothesis (1997) is that the amounts of carbon that can be associated with clay and silt particles is limited. Was observed that although the arable soils contained less carbon than the corresponding grassland soils, the amounts of carbon associated with clay and silt particles was the same indicating that the amounts of carbon that can become associated with this fraction had reached a maximum.

Was also observed close positive relationships between the proportion of primary particles < 20 mm in a soil and the amounts of carbon that were associated with this fraction in the top 10 cm of soils. The amount of carbon in the fraction > 20 mm was not correlated with soil texture. Cultivation decreased the amount of carbon in the fraction > 20 mm to a greater extent than in the fraction < 20 mm, indicating that carbon associated with the fraction < 20 mm is better protected against decomposition. Later it was proposed to estimate the carbon protection capacity (CPC) of the soil and the fraction of particles < 0.05 mm and also to take into account the mineralogical composition of the soil (Six et al., 2002).

MATERIALS AND METHODS

Research was conducted at the Ukrainian Natural Steppe Reserve (UNSR) «Mykhailivska Tsilyna» of Lebedyn district, Sumy region in the northeastern part of the Forest-steppe zone of Ukraine (882.9 ha). UNSR «Mykhailivska Tsilyna» have been virgin soil since 1928 (202.5 ha). The fallow more than 20 years (134.9 ha), the mow the grass virgin soil more than 20 years (46.1 ha). Soil sampling was conducted at the UNSR «Mykhailivska Tsilyna» of have been done in autumn at 2020 on 3 plots (Figure 1).

The climate of the region is temperate continental with an accumulated temperature of 2850°C. The vegetation period (days with an average daily temperature above 6.6°C) is 180-210 days. The average annual precipitation is 600 mm. Soil - chernozem typical heavy loamy with pH_{KCl} = 5.76, bulk density = 1.10 g/cm^{-3}, the amount of absorbed bases is 23.0 meq per 100 g of soil, soil organic carbon content = 4.69-5.39%.

Figure 1. Soil sampling points in the Ukrainian Natural Steppe Reserve «Mykhailivska Tsilyna»

Also research was conducted at the long-term field experiment was conducted on Typical Chernozem at Institute of Vegetables and Melons NAAS of Ukraine, Selektsiine village, Kharkiv District, Kharkiv Region. Experimental field is located in Forest-Steppe zone of Ukraine. The territory of experimental fields is characterized by a temperate continental climate. The sum of positive temperatures is about 2850°C. The vegetation period (days with an average daily temperature above 5°C) is 195-220 days. The average annual precipitation is 560 mm. Soil – chernozem typical heavy loamy with pH = 5.7, bulk density = 1.30 g/cm^{-3}, the amount of absorbed bases is 26.0 meq per 100 g of soil, soil organic carbon content = 2.49%.

Experimental plot were irrigated by sprinkler irrigation system during 55 years (2-4 times per year with the norm of 350-500 m^3/ha^{-1}). An each experimental plot was 58.3 m^2 with 4 replicates. In all variant of experiment plow tillage was applied. Sampling locations varied in terms of fertilization: without fertilizer (control), mineral fertilization system, organic fertilization system, organo-mineral fertilization system.

Crop rotation: barley - cucumber - winter wheat - onion - tomato - cabbage - beetroot. $N_{540}P_{510}K_{450}$ (mineral fertilization system), manure 189 t/ha^{-1} (organic fertilization system), 126 t/ha^{-1} of manure + $N_{330}P_{330}K_{450}$ (organo-mineral fertilization system) were applied for rotation. Soil sampling was carried out in autumn 1967-2022.

The chernozem samples were taken from the depth of 0-30 cm. Organic carbon content was determined by Tyurin method based on dichromate oxidation (DSTU 4289:2004), density of structure according to DSTU 5096:2008, granulometric composition of soil (DSTU 4730:2007). All measurements were performed in triplicate. For the calculation of SOC stocks was the basic formula:

SOC_{stocks} (t/ha) = h × 10000 × p × d / 100, where h – layer of soil, m, p – soil carbon content, %, d – bulk density, g/cm^3 (Viatkin et al., 2019).

The carbon protection capacity of typical chernozem was determined according to Hassink (1997) and Six et al. (2002) based on data of the fine fractions content and the mineralogical composition of soils. The carbon saturation degree of soils were calculated according to Meyer et al. (2017) and Wiesmeier et al. (2014).

RESULTS AND DISCUSSIONS

Physicochemical characteristics inherent to typical chernozem define the maximum protective capacity which limits increases C sequestration with changes in land management. With decreasing C_{org} content in top layer of typical chernozem on long-term field experiment crop cultivation under mineral, organic and organo-mineral fertilization system also observed decreasing associated with the fraction < 0.02 mm and < 0.05 mm size content carbon was found (Table 1).

It should also be noted that when changing land use or farming system after a certain period (50 years), a quasi-stationary state of carbon is established in the soil the balance between of mineralization and stabilization processes is achieved. Studying the dynamics of changes C_{org} content in the 0-30 cm layers of typical chernozem at the long-term field experiment with irrigation system show that after a decrease in the content over 35 years (1980-2015), there is an accumulation and stabilization of the carbon content (Figures 2-5).

Table 1. C_{org} content and bulk density in the 0-30 cm layer of typical chernozem

Tillage	Land use type	C_{org} content, %	Bulk density, g/cm^3	C_{org} content, g C kg^{-1}	
				< 0.02 mm size	< 0.05 mm size (MOM)
The Ukrainian Natural Steppe Reserve «Mykhailivska Tsilyna»					
Without tillage	The fallow (›20 years)	3.8	1.2	3.00	22.8
	Mow the grass virgin soil (›20 years)	4.0	1.2	3.20	24.0
	Absolute virgin soil (›95 years)	4.8	1.1	3.80	28.8
Long-term field experiment at Institute of Vegetables and Melons NAAS of Ukraine					
Plowing 0-25 cm	Without fertilizer (›50 years)	2.44	1.4	1.95	14.64
	Mineral fertilization system (›50 years)	2.50	1.3	2.00	15.00
	Organic fertilization system (›50 years)	2.58	1.2	2.06	15.48
	Organo-mineral fertilization system (›50 years)	2.63	1.2	2.10	15.78

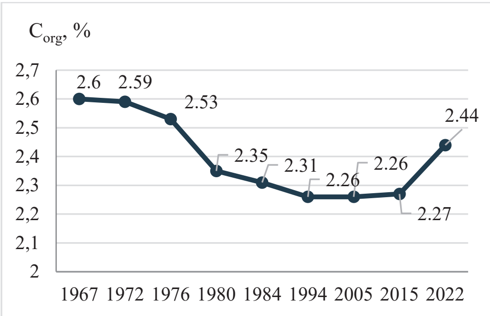

Figure 2. Dynamics of changes C_{org} content in the 0-30 cm layers of typical chernozem without fertilizer

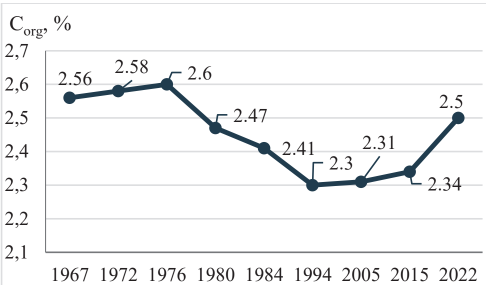

Figure 3. Dynamics of changes C_{org} content in the 0-30 cm layers of typical chernozem under mineral fertilization system

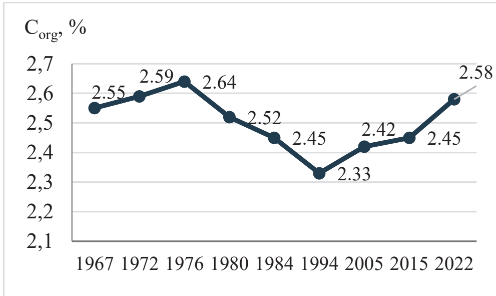

Figure 4. Dynamics of changes C_{org} content in the 0-30 cm layers of typical chernozem under organic fertilization system

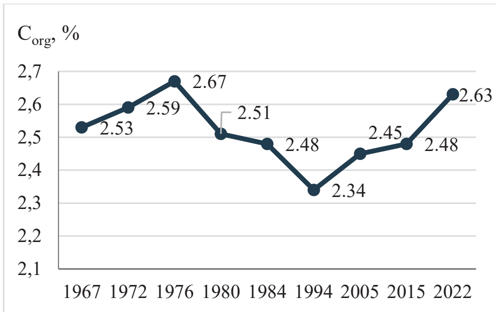

Figure 5. Dinamics of changes Corg content in the 0-30 cm layers of typical chernozem under organo-mineral fertilization system

The SOC losses within thirty five years were spatially variable and varied between 9% and 13% relative to the initial SOC content under crop cultivation without fertilizer and between 1% and 10 % under fertilization system.

Each land-use system has a different time for C_{org} stabilization. So, when cultivation of crop without fertilizer between a significant decrease and stabilization 42 years have passed (1980-2022), under mineral and organic fertilization system - 42 years (1980-2022), under organo-mineral fertilization system - 35 years (1980-2015).

These data indicate that the high ability of typical chernozem to stabilize SOC. But reach the level of C_{org} content (3.8-4.8%) approximately like virgin soils is not possible without additional agricultural practices.

The relationship between soil structure and the ability of soil to stabilize soil organic matter (SOM) is a key element in soil C dynamics. SOM can be physically stabilized, or protected from decomposition, through microaggrega-tion, or intimate association with silt and clay particles, and can be biochemically stabilized through the formation of recalcitrant SOM compounds (Six et al., 2002).

These processes can be achieved through land use change. This requires a transition from plowing to disking and the introduction of organic additives that contribute to the long-term preservation of SOM as a result of biological and physicochemical conditions. It was established that the plowing of typical chernozem led to the formation of a fulvato-humate type of humus due to the accumulation of fulvic acids which causes weak fixation and stabilization of newly formed organic substances (Popirny, 2016).

Disking of typical chernozem caused an increase in the content of humic acids, caused the formation of humate type of humus and increases the depth of humification which increases the stability of the humus system.

Was estimate the maximum amounts of C that can be associated we compared the degree of carbon saturation (DCS) virgin soils (fallow, mow the grass virgin soil, absolute virgin soil) with arable soils of typical chernozem.

For more than 50 years of agricultural use of typical chernozem the soil contained on average 25.3 g SOC kg^{-1} compared to virgin soils were lost 16.7 g kg^{-1} it was found (Table 2).

The adsorption of organics to fraction < 0.05 mm of particles is an important determinant of the stability of organic matter in soils but the amounts of C that can be associated with fraction < 0.05 mm of particles is limited. This study quantifies the relationships between soil texture and the maximum amounts of C that can be preserved in the soil by their association with fraction < 0.05 mm of particles.

Measuring the contents of SOC and the contents of SOC in the fraction of particles < 0.05 mm allows calculated the carbon protection capacity (CPC) and carbon saturation degree (CSD) in the 0-30 cm layer of typical chernozem by formulas:

$CPC = 3.86 + 0.41 \times (S + C)$ (1);

$CSD = CPC – MOM$ (2);

$DCS = (1 – (CSD / CPC)) \times 100$ (3).

By indicators DCS it can be seen that of carbon sequestration potential of arable soils is 56-61% used of the possible potential. The stocks of organic carbon present in virgin soils represents a dynamic balance between the input of dead plant material and loss from decomposition (mineralization) and it 136-158 t/ha.

In arable soils related these parameters to SOC losses in the 0-30 cm layer of typical chernozem and amount to no more than 92-102 t/ha. Despite these indicators in arable soils increases proportion of granulometric particles < 0.05 mm which stabilized and protected from decomposition in the soil characterizes the CPC of the soil.

Table 2. Characteristics of carbon sequestration capacity and SOC_{stocks} in the 0-30 cm layer of typical chernozem

Land use type	S + C	C_{org} content	CPC	CSD	DCS	SOC_{stocks}
	%	g C kg^{-1}		%		t/ha
The Ukrainian Natural Steppe Reserve «Mykhailivska Tsilyna»						
The fallow	61.61	38	29.12	6.32	78	136.8
Mow the grass virgin soil	49.40	40	24.11	0.11	99.5	144.0
Absolute virgin soil	49.40	48	24.11	-4.69	119	158.4
Long-term field experiment at Institute of Vegetables and Melons NAAS of Ukraine						
Without fertilizer	52.40	24	25.34	10.70	58	102.5
Mineral fertilization system	52.70	25	25.47	10.47	59	97.5
Organic fertilization system	58.36	26	27.79	12.31	56	92.9
Organo-mineral fertilization system	53.45	26	25.77	9.99	61	94.7

Note. S + C – proportion of granulometric particles < 0.05 mm, % of the soil; C_{org} – total soil organic carbon content; CPC – carbon protection capacity; CSD – carbon saturation degree; DCS – degree of carbon saturation.

CONCLUSIONS

Long term agricultural practices such as deep tillage and irrigation under different fertilization system in crop rotation to decline in soil organic carbon content compared virgin soil by 16.7 g kg^{-1}, SOC stocks content also decreased average by 49.5 t/ha. Virgin typical chernozem in the 0-30 layer on average contained C_{org} 1.6 times, more than arable soil.

The CPC value of soils is practically independent of land use type, amounting to 25.34-27.79 and 24.11-29.12 g C kg^{-1} under arable and virgin soils.

Returning the lost soil carbon via increasing carbon storage in soils is a clear sequestration possibility and the potential increases in soil carbon associated with land-use changes. Arable soil can play a significant role in atmospheric CO_2 sequestration if converted to fallow soil or change soil management and farming systems.

Restoring soil quality necessitates increasing SOC concentration by adopting best management practices (application organic amendments, conservation agriculture, minimizing tillage) which create a positive carbon budget.

The finding of a typical chernozem having a maximum capacity to preserve organic carbon will improve our estimations of the amounts of carbon that can become stabilized in soils. It has important consequences for the contribution of different soils to serve as a sink or source for C in the long term.

REFERENCES

Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., & Smith, P. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, *3*, 1-8. doi: 10.1038/s41893-020-0491-z.

Cambardella, C. A., & Elliott, E. T. (1993). Methods for physical separation and characterization of soil organic matter fractions. *Geoderma*, *56*, 449–457. https://doi.org/10.1016/0016-7061(93)90126-6.

Doetterl, S., Stevens, A., Six, J., Merckx, R., Oost, K. V., Pinto, M. C., Casanova-Katny, A., Muñoz, C., Boudin, M., Venegas, E. Z., & Boeckx, P. (2015). Soil carbon storage controlled by interactions between geochemistry and climate. *Nature Geosci*, *8*, 780–783. https://doi.org/10.1038/ngeo2516.

Gamaley, V. I., Dragan, M. I., Shkarivska, L. I., & Didora, V. G. (2010). The state of typical chernozem under organic farming. *Bulletin of Agricultural Science*, 12, 48–51.

Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil*, *Vol. 191*, 77–87. doi: 10.1023/A:1004213929699.

Ingram, J. S. I., & Fernandes, E. C. M. (2001). Managing carbon sequestration in soils: concepts and terminology. *Agriculture, Ecosystems & Environment*, *87*, 111–117. https://doi.org/10.1016/S0167-8809(01)00145-1.

Lal, R., Negassa W., &Lorenz, K. (2015). Carbon sequestration in soil. *Current Opinion in Environmental Sustainability*, *15*, 79–86. https://doi.org/10.1016/j.cosust.2015.09.002.

Mbanjwa, V. E., Hughes, J. C., & Muchaonyerwa, P. (2022). Organic Carbon and Aggregate Stability of Three Contrasting Soils as Afected by Arable Agriculture and Improved Pasture in Northern KwaZulu-Natal, South Africa. *Journal of Soil Science and Plant Nutrition*, *22*, 2378–2391. https://doi.org/10.1007/s42729-022-00815-x.

Meyer, N., Bornemann, L., Welp, G., Schiedung, H., Herbst, M., & Amelung W. (2017). Carbon saturation drives spatial patterns of soil organic matter losses under long-term bare fallow. *Geoderma*, *306*, 89–98. https://doi.org/10.1016/j.geoderma.2017.07.004.

Plaza-Bonilla, D., Álvaro-Fuentes, J., & Cantero-Martínez, C. (2014). Identifying soil organic carbon fractions sensitive to agricultural management practices. *Soil & Tillage Research*, *139*, 19–22. https://doi.org/10.1016/j.still.2014.01.006.

Popirny, M. A. (2016). Changes in the qualitative and spectroscopic characteristics of the organic matter of typical chernozem under various tillage systems. *Bulletin of Agricultural Science*, *7*, 65-68. https://doi.org/10.31073/agrovisnyk201607-12.

Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, *241*, 155–176. https://link.springer.com/article/10.1023/A:1016125726789.

Six, J., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology & Biochemistry*, *32*, 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6.

Stockmann, U., Adams M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A. B., de Courcelles, V. R., Singh, K., Wheeler, I., Abbott, L., Angers, D. A., Baldock, J., Bird, M., Brookes, P. C., Chenu C., Jastrow J. D., Lal R., Lehmann J., O'Donnell A. G., Parton W. J., Whitehead, D., & Zimmermann, M. (2013). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment, 164*, 80–99. https://doi.org/10.1016/j.agee.2012.10.001.

Viatkin, K. V., Zalavskyi, Y. V., Lebed, V. V., Sherstyuk, O. I., Bihun, O. M., Plisko, I. V., &

Nakisko, S. G. (2019). Digital mapping of soil organic carbon stocks in Ukraine. *Soil Science*, *88*, 5–11.

Virto, I., Barre, P., Burlot, A., & Chenu, C. (2012). Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. *Biogeochemistry*, *108*, 17–26.

Wiesmeier, M., Hübner, R., Spörlein, P., Geuß, U., Hangen, E., Reischl, A., Schilling, B., von Lützow, M., & Kögel-Knabner, I. (2014). Carbon sequestration potential of soils in southeast Germany derived from stable soil organic carbon saturation. *Global Change Biology*, *20*(2), 653–665. https://doi.org/10.1111/gcb.12384.