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DYNAMICS OF SOIL ORGANIC CARBON AFTER MORE THAN 25 YEARS OF FARMING IN THE DANUBE DELTA

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Abstract: Soil organic carbon (SOC) is an important parameter in the context of global warming, and a special attention should be given to its dynamics. The purpose of this paper is to test the existence of SOC losses from the soils taken for farming for more than 25 years in some areas of the Danube Delta. Another objective is to quantify such SOC losses if they exist. The studied soils belong to two land reclamation areas, Carasuhat and Dunavat, from the Danube Delta. Data of present-day SOC stocks were compared to the SOC stocks calculated for the period until year 1996 for the same soil units in order to assess the dynamics of SOC losses for more than 25 years. We have found that a specific process was noted for the organic soils, Histosols, which were turned into histic soils after farming, meaning that there was a significant decrease in SOC pool. Thus, SOC losses due to farming were maximum for Histosols, and SOC stocks were highly significantly lower in 2022 versus 1996, due to increasing mineralization processes of organic matter and subsequent greenhouse gas emissions that occurred in cropland areas. Relationships have been found quantifying SOC losses versus the original 1996 stocks, confirming that Histosols, containing the maximum SOC stocks, present the highest risk of degradation. Lowering of the ground water and consequently the intensified oxidation of peat are very important factors in SOC losses beside the agricultural land use works. Policy makers, decision makers and stake holders should promote conservation of the natural landscape of the Danube Delta in order to increase SOC stocks and decrease CO_2 and other greenhouse gas emissions into the atmosphere. Maintaining the former SOC stock at the present-day level and enhancing new organic C sequestration in the renatured parts of the less fertile Delta soils could contribute to global warming mitigation in the future and to supply agricultural products in the cropland already in use. Future research in characteristic stationary sites of the Danube Delta, especially in the farmland area, is recommended to improve our knowledge on SOC evolution.

Keywords: wetland ecosystem, crop environment, carbon sequestration, carbon loss, Histosols, histic soils

1. INTRODUCTION

Organic carbon – an essential component of organic matter - soil-texture, soil structure, pH and soil nutrients' content are among the most important soil properties. Some of these properties correlate with each other under specific natural conditions. In Romania, Florea (1962) and Vintilă et al., (1963) found a direct correlation between the humus content and the clay content for some zonal, mineral soils like chernozems, while Obrejanu et al., (1964) found a similar correlation for the Danube Flood Plain soils. Vintilă et al. (1984) reported a synthesis of soil humus content in different arable soil types and textures in Romania as well as its spatial distribution for the 0-0.5 m depth. Quite recently, Vintilă & Radnea (2018) produced a map describing soil humus content over the whole area of Romania using both local data and pedotransfer functions for topsoil.

Carbon sequestration in soils occurs as soil organic carbon (SOC) as well as soil inorganic C (SIC). Heiri et al., (2001), Boyle (2004) and Lal et al., (2015), among others, described how SOC is sequestrated in various soils worldwide. SOC content generally depends on land use, soil management and farming systems (Lal et al., 2015). SIC is usually sequestrated in calcium and magnesium carbonates (Lal, 2015).

For mineral soils, older Romanian studies showed that comparing the agriculture soils with unfarmed soils, investigations showed a decrease of about 56-70% in soil humus content of arable soils versus forest and pasture soils (Florea & Vlad, 1970; Vintilă et al., 1984).

Internationally, cropland soils are considered depleted of SOC due to intensive agricultural practices (Paustian et al., 2019), the carbon lost due to such practices nearly equaling the present stocks (Sanderman et al., 2017). Thus, SOC is a very important parameter for understanding, modeling and mitigating of global warming, and a special attention should be given to its dynamics. Through "mean residence time", Lal et al., (2015) defined the time when C pool is sequestrated in the soil until released into the atmosphere. They also recommended the best management practices of conservation agriculture that induced a positive C budget in the environment.
Among the most representative landforms containing large amounts of SOC are wetlands and especially river deltas (e.g. Tolonen & Ijäs, 1982; Karesniemi, 1972; Grigal et al., 1989; Munteanu, 1996; Bauer et al., 2006, Mocanu et al., 2022), and such an impressive delta is the Danube Delta. As a matter of fact, due to the anoxic conditions that slow down or even inhibit decomposition, wetlands can store up to 40% carbon, a much larger amount that is commonly found in agricultural soils (Nahlik & Fennessy 2016). SOC is also well sequestrated in other soil types, such as forest soils (Liu et al., 2017; Panakoulia et al., 2017; Chatterjee et al., 2018; Parsapour et al., 2018; Paltineanu et al., 2020).

Many scientists studied the Romanian part of the Danube Delta in the XXth century from various viewpoints (Coteț, 1960; Panin, 1974, 1983; Gâstescu et al., 1983; Gâstescu & Dringa, 1989; Munteanu et al., 1989; Hanganu et al., 1994). Mocanu et al., (2022) described in detail the soil cover of the Danube Delta ecosystem and quantified SOC pools from both organic and mineral soils for various soil depths.

About 15% of the Danube Delta soils were used as agricultural lands (Mocanu et al., 2022), generally starting from 1980 (Hanganu, 2008) and mainly as arable soils. These soils were subject to intense transformation after changing from a natural environment to an agricultural land use (Hanganu, 2008), specifically through diking, drainage, and plowing. As a result, increased emissions of CO_2 usually occurred (Munteanu, 1996). Soil fertility thus decreased due to SOC mineralization and acidification. Nevertheless, a SOC loss quantification in time caused by farming has not been done yet for this region.

The purpose of this paper is to test the existence of SOC losses for various soil depths from the soils taken for farming for more than 25 years in some areas of the Danube Delta, and to quantify such SOC losses if they exist.

2. MATERIAL AND METHODS

According to Köppen's climate classification system (Geiger, 1961), the climate of the Danube Delta is at a transitory area between boreal DFa and arid cold-steppe BSk. Sunshine hours in the region, between 2200 and 2300, are among the highest in Romania (Paltineanu et al., 2000; 2002). A trend of climate warming generating an advance in phenological phases of crops have been recently noted for the southern part of Romania (Chitu & Paltineanu, 2020; Paltineanu & Chitu, 2020).

The studied soils belong to two representative land reclamation areas, Carasuhat and Dunavat from the Danube Delta (Figure 1), where dikes and drainage canals were previously built as measures to enable farming. Figure 1 presents the soils from the studied areas of the Danube Delta as well as the locations of the soil profiles. The soils are mainly Fluvisols (Gleyic-calcaric, Marshy-Fluvic-Eutric, Gleyic-Eutric, Fluvic-Mollic, and Marshy-Fluvic-Mollic subtypes) and Histosols (Terric, Terric-thionic and Thionic subtypes), as reported by Munteanu (1996) and Mocanu et al., (2022). The soils classified after WRB (2014) were grouped according to the strength of the histic character.

Soil profiles were carried out in both mentioned land enclosures, in field campaigns of 2021-2022 organized by ICPA Bucharest in collaboration with OJSPA Tulcea. Soil samples were taken and analyzed from 30 profiles studied for various properties according to the standard methods used in Romania. Sampling was from each soil horizon of the profiles and analyses were carried out in the laboratory of ICPA Bucharest. A number of cca. 50 boreholes were also carried out to test soil types' spread. This number of current 30 soil profiles cover the Carasuhat and Dunavat areas, which represent a small area of only 6,191 ha, whereas the profiles number studied for the entire Delta of 385,469.05 ha (soil area only) covering the studies from 1996 and 2022 was much greater, i.e. 1011 soil profiles plus over 4000 soil boreholes (Munteanu, 1996; Mocanu et al., 2022). Consequently, the area/profiles ratio was cca. 381 ha/profile or 77 ha/(profiles + boreholes) for the whole Delta whereas 206 ha/profiles or 76 ha/(profiles + boreholes) for the Carasuhat and Dunavat areas. The order of magnitude for these ratios is not much different, allowing thus confident comparisons.

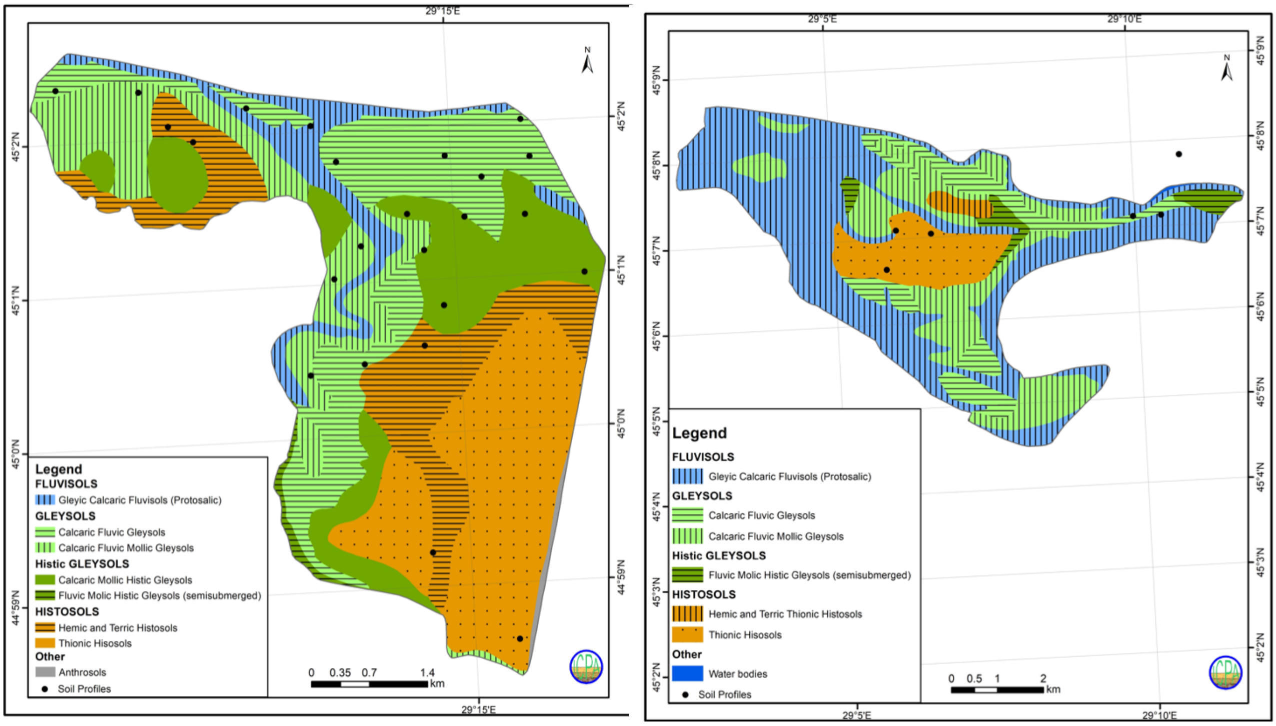

Figure 1. Soil map of Dunavat (left) and Carasuhat (right) areas in the Danube Delta showing locations of the soil profiles analyzed in 2022 (extract from the map published by Mocanu et al., 2022)

Among the main soil properties analyzed are pH (SR 7184-13: 2001), base saturation (STAS 7184/12-88), organic C content and organic matter (Walkley-Black method modified by Gogoasa, STAS 7184/21-82 standard and loss-on-ignition method for peat), bulk density (BD) (SR EN ISO 11272: 2014), NPK content (Kjeldahl method STAS 7184/2-85 standard, Egnèr-Riehm-Domingo method). The soils have been combined into three major groups such as: Histosols, histic Gleysols and non-histic Gleysols and Fluvisols, taking into account the previously related paper (Mocanu et al., 2022), and the fact that the histic character is the main soil feature studied in analyzing the SOC pool.

SOC stocks (Mg/ha) were first calculated for soil horizons by multiplying SOC contents (% kg/kg) with soil depth (cm) and BD (kg/dm^3), and then as weighted averages for various depths and soil units. Afterwards these values were compared to the SOC stocks calculated for the period until year 1996 for the same soil units as presented by Mocanu et al. (2022), in order to assess the dynamics of SOC loss for this period of more than 25 years.

Comparisons were carried out through ANOVA in SPSS 14. The means followed by different letters are significant for various probability levels ($p \leq 0.05$ significant * or just one letter, $p \leq 0.01$ distinctly significant ** or two letters, or $p \leq 0.001$ highly significant *** or three letters). In the present case the emphasis was put on the comparison between the SOC stocks at the same depths between these two situations: 1) until 1996 and 2) in 2022. Regression equations were calculated using Microsoft Office Excel Program and the least squares method, and the correlation coefficient (R) was tested for significance using the t-test in comparison with tabulated values at the significance level, using a two-sided t-test and (n - 2) degrees of freedom (Aïvazian, 1970).

3. RESULTS AND DISCUSSION

3.1. Main soil properties

Table 1 presents some of the main soil properties of two representative soils of the studied area, both mollic-histic Gleysols, situated in Dunavat and Carasuhat areas, respectively. The soil chemical reaction, pH, is slightly alkaline for the Dunavat mollic-histic Gleysol until the TGr2 horizon where SOC content is as high as 29% and where pH is moderately acid. The Carasuhat mollic-histic Gleysol is generally slightly acid to neutral, with a relatively uniform SOC content down to 0.8 m depth, i.e. a CGr horizon slightly alkaline and poor in SOC. For most of the studied soils pH mostly varied within this range.

Even if the clay content is high for both soils as percentage of mineral matter, with more than 55% for most of the horizons, BD values characterize these soils as highly porous and non-compacted soils, where SOC is specifically high (the last two horizons

Table 1. Soil horizons and some of the main soil properties: pH, SOC, BD and clay content for two mollic-histic Gleysols at Dunavat and Carasuhat areas from the Danube Delta, after taken for farming for more than 25 years

Location/Soil Type	Soil Horizon Symbol	Depth (cm)	pH	Soil Organic Carbon Content (%)	Bulk Density (g/cm^3)	Clay content (<0.002 mm)
*Dunavat, Mollic-histic Gleysol	Ap	0-20	8.03	3.57	1.10	62.7
	A/CGox	20-30	7.69	3.71	1.15	62.3
	CGox	30-48	7.54	4.63	1.11	66.3
	A/C	48-60	7.69	2.80	0.81	59.9
	TGr1	60-85	7.34	13.0	0.50	66.9
	TGr2	85-110	5.73	29.4	0.31	68.3
Carasuhat, Mollic-histic Gleysol	At	0-18	6.42	13.5	0.62	56.4
	Am	18-32	6.64	11.8	0.44	57.1
	AmGr	32-55	6.95	12.6	0.40	53.1
	A/CGr	55-80	6.91	18.9	0.34	61.8
	CGr	80-110	7.78	1.44	1.00	42.3

at Dunavat and mostly all horizons at Carasuhat). A special remark should be done here, for the Carasuhat mollic-histic Gleysol that originated from a former natural Thionic Histosol, which changed due to farming during the last quarter of a century, most probably due to some specific processes of mineralization of organic matter and subsequent greenhouse gas emissions, or even due to peat burning. Thus, the present-day SOC content decreased significantly versus the 1996 situation and did not meet the criteria for a Histosol, as this soil type used to be there until 1996 and how was presented in the map of Figure 1. Aspects from these two soil profiles are presented in Figure 2, where dark-color, SOC-rich horizons and shallow groundwater can be seen as well as the vegetation growing above them.

As mentioned above, these soils are loosened, non-compacted, very permeable, allowing nutrients and pesticides to easily flow toward the ground water, as generally described for other permeable soils by Lacatusu et al., (2019), Domnariu et al., (2020), and Paltineanu et al., (2021, 2022). From this point of view of pollution hazard, these soils are under a potentially severe risk. These soils are also fertile, where all kinds of crops such as cereals, sunflower, sugar beet, soybean, other field crops and even fruit trees grafted on dwarf rootstocks may find sufficient root space (almost 1 m depth above water table) to thrive, as previously reported Paltineanu et al., (2017). There is a strong connection between the food system and climate change, the latter threatening availability of food, while the former contributing to the climate crisis. In light of this interference, fertility of these soils and continuing farming are to be judged versus renaturation of some less fertile soils, which might however, facilitate a higher, similar SOC pool, as prior to cropping.

3.2. Comparison between SOC stocks from 1996 and 2022

Figure 3 shows the comparison between SOC stocks for the studied soil types, between years 1996 and 2022, during which they were used as farmland, for five soil depths: 0-20, 0-30, 0-50, 0-100 and 0-150 cm. In the case of Histosols (Figure 3 up), the SOC pool decreased highly significantly from 1996 until 2022 for the first four soil depths, and distinctly significantly for the 0-150 cm depth. The cause of decrease could be represented by the increase in mineralization processes of organic matter and emissions of greenhouse gases such as CO_2 as well as by other specific processes governing peat transformation.

The percentage of actual SOC ranged from 28% for the 0-150 cm depth to 46% for the 0-20 cm depth. In other words, more than 50% of the SOC pool disappeared between 1996 and 2022 in the case of Histosols, i.e. the soils sequestrating the highest amount of organic C.

There was also a drop in the SOC pool for the histic Gleysols (Figure 3, left down). However, this decrease was lower and non-significant for all soil depths, as much as 59 to 86% for the 0-20, 0-30 and 0-50 cm depth, and with a non-significant increase in SOC for the 0-100 cm depth. Deeper than 1 m depth there was no practically SOC content for these soils.

This finding means that the histic Gleysols, containing much less SOC than Histosols, generally showed less and non-significant decreases in SOC pool, and the slightly increase for the 0-1 m depth is rather attributed to soil spatial variability, generally greater for the Delta and flood plain soils compared to the so-called zonal soils. The differences caused by spatial variability

Figure 2. Mollic-histic Gleysols soil profiles (left) at Dunavat (up) and Carasuhat (down), where the dark-colored horizons show high SOC content values, with ground water within about 0.9-1.0 m depth; wheat and rye cereals grow on these soils where water is available during most of the growing season

might also stem from the fact that the comparisons were done between the present-day SOC stocks in the analyzed profiles and the soil units from 1996, not versus the same points in these units. A higher precision might be obtained from future experiments that consider similar locations rather than soil units.

The non-histic Gleysols and Fluvisols from the studied areas showed practically no change or very slightly modifications regarding their SOC stocks (Figure 3, right down), with non-significant differences between the two situations.

The comparisons shown above also indicate the high differences between soils' behavior during farming. The larger the SOC pool in the soils the higher the SOC pool losses. Histosols consequently suffered the most severe changes when taken to farming and this conclusion should firmly be considered if and when such organic soils are to be turned into agricultural land.

3.3. Correlations between SOC losses in 2022 as a function of SOC stocks in 1996

Figure 4 shows the relationships between SOC losses in year 2022 as a function of the "original" SOC stocks in year 1996 for the five soil depths of the studied soils. For the first three soil depths: 0-20, 0-30 and 0-50 cm depths (Figure 4, left), where the roots of crops and wild flora usually develop the main volume, these relationships are highly significant and close to each other. For the last two soil depths, 0-100 and 0-150 cm, the relationships are also highly significant, even if there were less data points.

The relationships quantify SOC losses versus the “original” (1996) stock and confirm that Histosols containing the maximum SOC stocks present the highest risk for its deterioration and for climate warming. It can be noted that for the other soils that present lower SOC stocks, like Fluvisols and some Gleysols, e.g. less than about 100 Mg/ha for the first three soil depths and less than circa 200 Mg/ha for the maximum depths considered (0-100 and 0-150 cm), respectively, the regression lines present negative values.

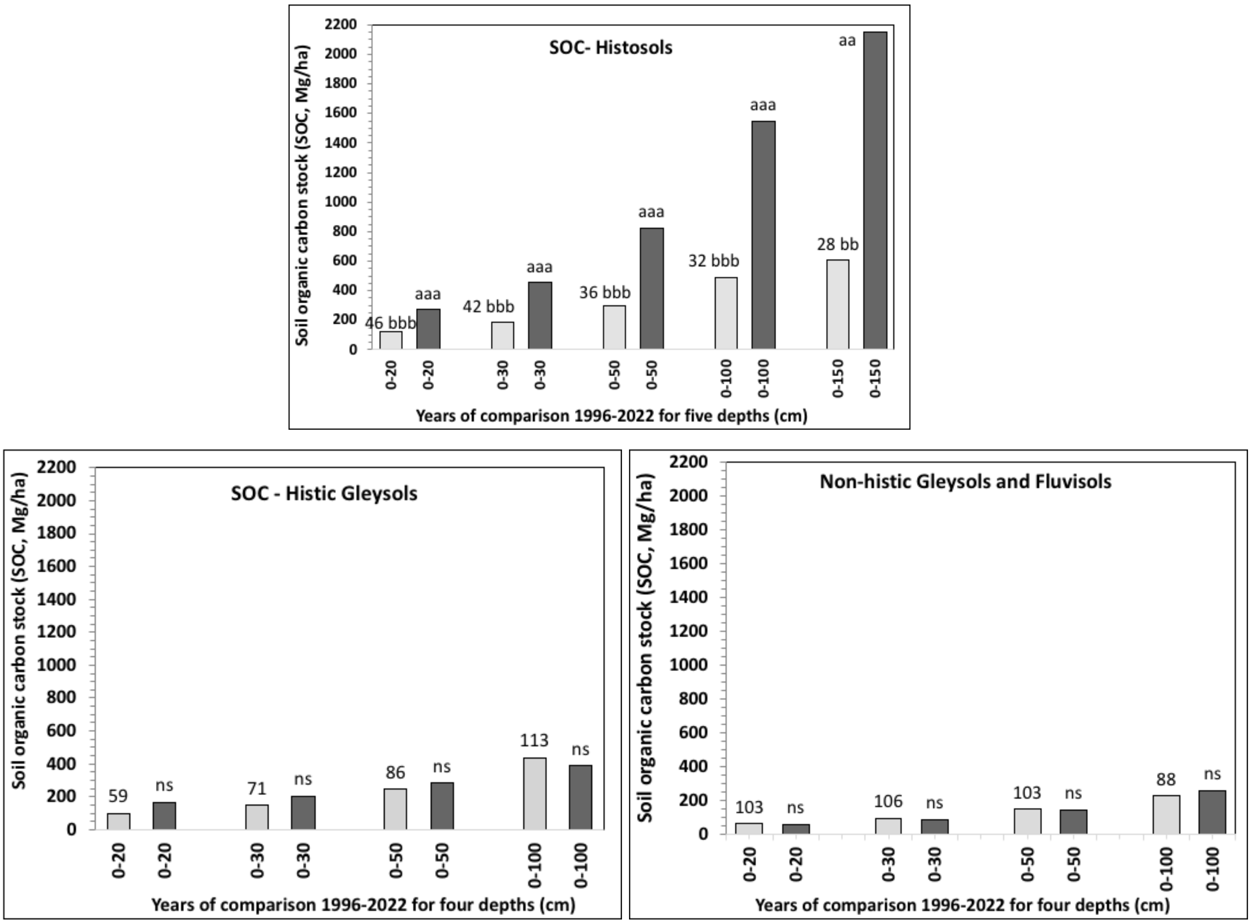

Figure 3. Comparison between SOC stocks for the studied soil types between years 1996 and 2022 for five soil depths: 0-20, 0-30, 0-50, 0-100 and 0-150 cm; dark columns represent 1996 while gray columns 2022. Comparisons are only done between these situations for the same depths, with different single letters showing significant differences, double letters as distinctly significant, triple letters as highly significant differences and ns as non-significant ones, while the figures above the gray graph columns show the SOC present-day pool percentage from the 1996 stock

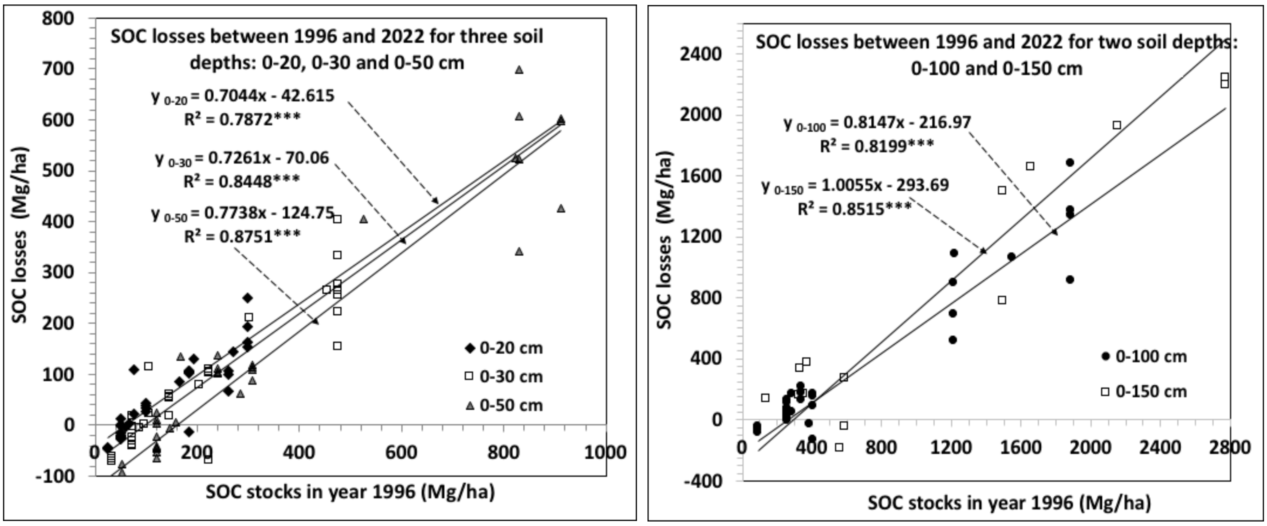

Figure 4. Relationships between SOC losses in 2022 as a function of SOC stocks in 1996 for five soil depths

This inconsistency is mainly attributed to the soil spatial variability, or SOC stability in mineral soils, and no real and non-significant SOC changes occurred for such soils during the investigated period.

The SOC losses discussed above cannot be distributed equally for the whole period to calculate an annual rate, because such losses usually occur in the first few years after land use conversion. Management practices may have played an important role regarding SOC stocks changes and greenhouse gas emission, particularly when a natural Histosol environment is turned into cropland and grassland, as Paustian et al., (1997), Conant et al., (2001), Ogle et al., (2004 and 2005), and Eleftheriadis et al., (2018) reported. According to Mann (1986) and Ogle et al., (2005), in the case of conversion from grassland and forest land to arable land there can be losses of circa 20-40%. The loss induced in wetlands conversion may be even higher, reaching up to 50%, as shown by Huang et al., (2010), similarly to our results.

After Armentano & Menges (1986), drainage of organic soils favors CO_2 emissions to the atmosphere. In drained soils, however, there is another specific process, namely one of decreasing of CH_4 emissions (Nykänen et al., 1995). Efforts have also been done to try to quantify greenhouse gas inventories for multiple land-use categories (Aalde et al., 2006; Lasco et al., 2006; Verchot et al., 2006), but mainly for the 0.3 m soil depth. Our paper quantifies and discusses SOC stocks losses for various soil depths, enabling thus to employ its conclusions for SOC dynamics models.

Happily, as already shown (Mocanu et al., 2022), only about 15% of the Danube Delta was turned from a natural environment into farmland, and this low percentage should remain as such, or even to decrease through a further renaturation process in a low-fertility area, such as the least fertile soils: Solonchaks, Solonetz and sands. SOC sequestration and preservation in natural wetland environment is a slow process, and this equilibrium has a benefic consequence (Gorham, 1991). More recently, Berthelin et al., (2022) reported that maximum 10% of added plant residues every year remain in soils after mineralization by soil microorganisms, and the released CO_2 is rapidly transferred to the atmosphere. One of the best recommendations is consequently to preserve the current extent of Delta's natural areas.

Nevertheless, if such soils were decided to be used for cropping, to limit SOC loss and to increase SOC content in agricultural fields, conservative management practices should be used. For example, reduced tillage and no-till management proved to increase SOC versus both intermediate intensity tillage and high intensity tillage in the upper soil horizons as shown by numerous scholars (Haddaway et al., 2017, Bai et al., 2019, Li et al., 2020), even if this situation might not be convenient for some farmers.

Future investigations might deepen our knowledge on the dynamics of SOC in wet areas. For instance, labile carbon stocks are considered more sensitive and important components of SOC (Bongiorno et al., 2019) that could better explain SOC sequestration (Wiesmeier et al., 2015) through the intense microbial activity (Vance & Chapin, 2001; Fissore et al., 2013).

As far as we found out about the climate evolution and the increase in temperature and frequent landscape fires all over the world, as also in 2022, a stronger global endeavor should be made to mitigate global warming, which would eventually generate sea level rising and flooding of coast settlements worldwide.

4. CONCLUSIONS

A comparative study has been done between the natural soils from year 1996 in two representative areas of the Danube Delta, Dunavat and Carasuhat, and the same soils that were taken for farming for more than 25 years long.

A specific process was noted specifically for the organic soils, Histosols, which were turned into histic soils after farming, showing a significant decrease in soil organic carbon (SOC) pool. SOC losses due to farming were maximum for Histosols, and SOC stocks were highly significantly lower in 2022 versus 1996, generally more than 50%, due to mineralization of organic matter and subsequent greenhouse gas emissions and other possible processes that govern peat transformation and that developed in farmland.

Lowering of the ground water and consequently the intensified oxidation of peat are very important factors in SOC losses beside the agricultural land use works. If such SOC losses will also be found through further studies in other farmland areas of deltas, then these findings might be generalized for other river deltas from temperate climate regions.

Relationships have been found that quantify SOC losses versus the original 1996 stocks and confirm that Histosols, containing the maximum SOC stocks, present the highest risk for deterioration and the highest contribution to climate warming.

The SOC losses cannot be distributed equally for the whole period to calculate an annual rate, such losses usually occurring more intensely in the first few years after land use conversion.

If the Danube Delta soils are used for farming, conservative management practices should be used to increase SOC content, because reduced tillage and no-till management proved to increase SOC in the upper soil horizons versus both intermediate-intensity tillage and high-intensity tillage, even if this situation might not be convenient for some farmers.

Policy makers, decision makers and stake holders should promote conservation of the natural landscape of the Danube Delta in order to increase SOC stocks and to decrease CO_2 and other greenhouse gas emissions into the atmosphere.

Maintaining the former SOC stock at the present-day level and enhancing new organic C sequestration in the renatured parts of the less fertile Delta soils could contribute to global warming mitigation in the future and supply agricultural products in the cropland used.

Future research in characteristic stationary sites of the Danube Delta, especially in the farmland area, is recommended to improve our knowledge on SOC evolution.

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