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Dynamics of carbon stock on fallow lands of black soils

Maria V. Tikhonova[1], Aleksey V. Buzylev[1], Yaroslava S. Zhigaleva[1], Marina A. Polshina[1,2]*

1. Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, 49 Timiryazevskaya St., Moscow, 127434, Russian Federation
2. Belgorod State National Research University, 85, Pobedy St., Belgorod, 308015, Russian Federation

* *Corresponding author's Email: E-mail: polshina@rgau-msha.ru*

ABSTRACT
The change in the carbon stock in the soil cover during the uplift of fallow areas on leached black soils is considered. The study compares carbon stock dynamics on fallow lands of black soils. Two objects of the study are in the central part of the Russian Federation in Penza region, which belongs to forest and forest-steppe climatic zones. Studies were carried out on two sites typical for the study area, differing in mesorelief and water regime. Object one is a fallow land of floodplain 30-year-old deposits with meadow vegetation characteristic of the region on meadow-black soil and leached black soil humus heavy loamy hydromorphic soils. The second fallow land is on 30-year-old deposits overgrown under a birch tree plantation with leached medium-humus heavy, loamy black soils. Four control sites were laid on each field, differing in the cultivation period. The carbon stock in the soil and the thickness of the arable horizon were estimated during the studies conducted. Greenhouse gas emissions were estimated using chambers that do not violate soil flows, and further analysis of the selected gases was performed on a chromatograph. The research results demonstrate the spatiotemporal dynamics of carbon dioxide emissions; the maximum values were tracked on a 30-year-old forest fallow site, and the minimum values on a meadow fallow ecosystem. The dependence of soil flows is associated with the warming of the soil cover, the density of soil horizons, and the fallowness of the territory since the amount of available carbon dioxide is increasing due to a large increase in vegetation biomass and litter. Carbon stocks in the arable horizon varied depending on the location of key sites in the relief, soil type, seasonality, and mechanized intervention of agricultural machinery.

Keywords: Fallow lands, Carbon reserves, Leached black soils, Carbon dioxide emissions.
Article type: Research Article.

INTRODUCTION
In the last five years, the Russian Government has been tasked with circling all abandoned lands that have ever been in agricultural use and are currently subject to afforestation, waterlogging, and tinning. Fallow territories occupy huge areas and have fertile lands in their potential, which are necessary to increase crop production and ensure the country's food security. There are variations in soil organic carbon estimates for both grasslands and woodlands. Some studies suggest that grassland soil carbon levels can exceed that of woodlands (Feyissa *et al.* 2010; Wei *et al.* 2012; Carbon 2022; Kriuchkov *et al.* 2023; Schuster *et al.* 2024). Some research focuses on the dynamics of carbon stock that do not vary significantly between forest or tree plantation and grassland. Carbon stock depends on the depth of the soil profile (Sharma & Kafle 2020) and the type of previous land use (Razanamahandry *et al.* 2022). However, most of the research on the amount of carbon stock is higher in soil with high stand density of trees such as forests or sparse forests (Sanderman & Amundson 2008; Saha *et al.* 2009;

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Yeasmin *et al.* 2020; Razanamahandry *et al.* 2022; Grasslands 2023). We decided to validate one of the concepts with our research. This study aimed to compare organic carbon stocks in fallow lands represented by grasslands and forests.

MATERIALS AND METHODS

The research was carried out in the central part of the Russian Federation in the Penza region. This region belongs to the Central Russian soil-geographical Province, Forest-steppe zone, and leached black soils subzone located in the southeast of the East European Plain. This subzone captures the territory of the Oka-Don lowland at the junction of forest and forest-steppe climatic zones. The Penza region has more than 1,300 thousand hectares of potentially suitable land for cultivating crops, which are currently listed as fallow, 31% of the area of the entire region (Fig. 1). In the Bashmakovsky district, where the research was conducted, fallow areas are represented by young deciduous forests that produce large amounts of oxygen and absorb carbon dioxide, which is the main greenhouse gas, the regulation of which is highlighted in the main Climate agenda. Also, part of the territory is represented by wetlands, where in turn act as a source of methane and nitrous oxide, which are also greenhouse gases.

Fig. 1. Location of the research region in the structure of chernozem soils (Global Black Soil Distribution Map - FAO 2021, INSB 2017).

The areas occupied by the main groups of soils are of different sizes, predominately of leached black soils (51.2 - 67.5%). Black soil-meadow and meadow-black soil, homogeneous to black soils in fertility, occupy 3.1%. Floodplain soils are found on 4.3% of the region's territory. The player-leached black soils studied in work occupy 40.6% of the black soil, those of the study region and 61.1% of all agroecosystems in the northern part of the Central Russian forest-steppe province, being the most common soil subtype of the analyzed territory. Monitoring studies were carried out on two sites typical for the study area (Fig. 2), differing in mesorelief and water regime. Four control sites were laid on each field, differing in the cultivation period. The first analyzed site, "Podgornoye" (P), is represented by a territory of floodplain 30-year-old deposits with an area of 20 hectares. It has meadow vegetation characteristic of the region on meadow-black soil and leached black soil humus heavy loamy hydromorphic soils. The second fallow site, Belozerka (B), is located on the territory of 30-year-old deposits overgrown with birch. The soil cover, which covers an area of 69 hectares, is represented by leached medium-humus heavy loamy black soils. As part of the agroecological assessment of territories, the main analyses were carried out by generally accepted standards and methods in the territory of the Russian Federation. The photometric termination of the instrumental methods was carried out on a LEKI SS2107UV spectrophotometer. The SevenCompact S220 potentiometer was used for potentiometric measurements. The mobile forms of potassium were determined using a flame photometer CL-378. Ecosystem respiration (g CO_2 m^2 day) periodically, by measuring the flow of CO_2 from the soil with a preserved plant layer using the method of ground exposure chambers - infrared gas analyzer Li6400, Li-Cor, USA with simultaneous sampling of gas into crimped glass vials (in three times repetition) for subsequent analysis on a Chromatek-Kristall 5000 gas chromatograph (Vasenev *et al.* 2014). Statistical data processing was carried out using the IBM SPSS Statistics software package.

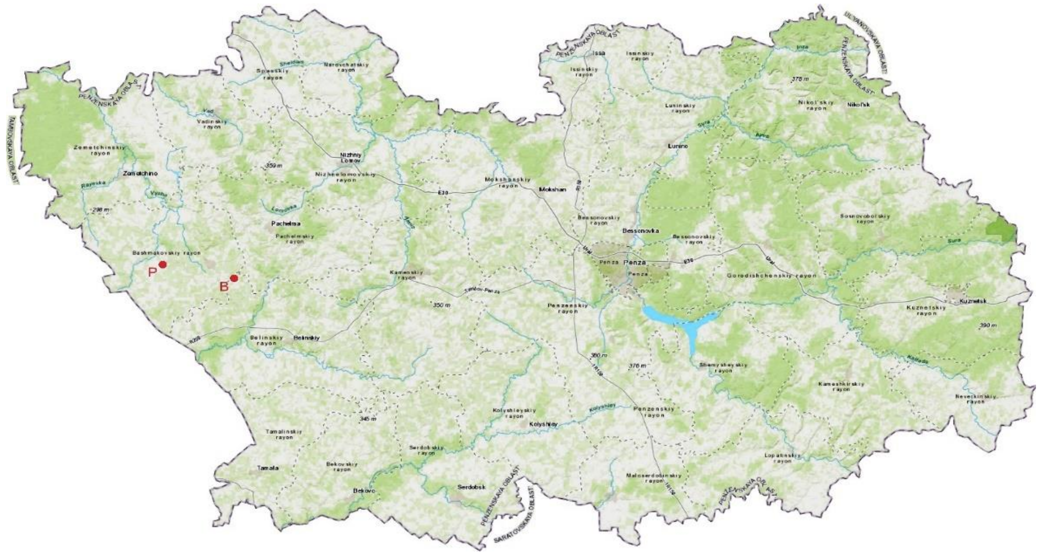

Fig. 2. The location of the experimental sites on the map of the Penza region: "Podgornoye" (P), "Belozerka" (B).

RESULTS AND DISCUSSION

The representativeness of the analyzed sites is a key factor in the significance of the research (Bulgakov *et al.* 2013). We compared current agroecological soil characteristics with reference characteristics corresponding to microrelief forms and the analyzed soil type to substantiate representativeness. The studied agroecosystem near the village of "Podgornoye" is a typical sloping watershed hill for the northwestern part of the Penza region with sloping slopes of all exposures without pronounced erosive manifestations with a steepness of up to 8°, often found in the transition zone of the Oka-Don lowland. The predominant exposure is the north-western one. The absolute heights are 155-177 m. The soil cover is represented by leached black soils, powerful humus, heavy loamy, not eroded on loess-like clays (Table 1), turning into meadow-black soil at the foot of the slope.

Table 1. Average indicators of agroecological characteristics of the arable horizon of agrogenically altered black soils of hydromorphic lands in the northwestern part of the Penza region (Kriuchkov *at al*. 2023).

Agroecosystem	Depth A (A arable + A 1)	$C_{org.}$ (%)	pH_{KCl}	Density (g/cm^3)	The amount of absorbed bases (ppm)	The degree of saturation of the bases (%)
Podgornoye	52	6 .7	5 .29	1 .27	35 .7	87 .6
Hilly accumulative landscape	54	7 .0	5 .29	1 .24	34 .5	86 .9
Hilly denudation landscape	52	6 .8	5 .56	1 .21	36 .4	87 .1

The main part of the analyzed area is dominated by the humus content in the arable horizon of 6.7%, with a variation from 6.5% to 7.9%, and a decrease in its content along the profile occurs at a depth of 45-60 cm, which is generally characteristic of the sloping black soils of the northwestern part of the Penza region. The thickness of the humus horizon is 80-120 cm, increasing to the base of the slopes in meadow-black soil areas. The soils are characterized by good physical properties, slightly varying depending on the parts of the slope and the forms of the microrelief. The boiling depth is from 10% hydrochloric acid, and the appearance of "white eyes" is noted from 126 cm (Tikhonova & Buzylev 2024). The microrelief is represented by forms of suffusion processes - saucers and semi-enclosed depressions, characterized by an increased (0.5-0.9%) humus content and elevated humidity of arable (2-4%) and sub-arable (4-6%) horizons. A comparison of the average agroecological characteristics of landscapes representative of the research area shows insignificant (V 5%) variations in the above indicators. It indicates the typicality and representativeness of the selected research object. The "Belozerka" postagrogenic ecosystem is a 30-year-old fallow site comparable in terms of relief conditions, which is being returned to intensive land use at the time of research. The territory is the lower third of the watershed hill with a gentle slope of 2-3° south-western exposure. At the foot of the hill, 100 m below the slope, there is a dammed bed of the old Lisiy stream, a tributary of the Belozerka River. The territory is deeply blackened. 63% was covered with 30-year-old birch trees, finally cut down in 2024. The soil cover of fallow lands is represented by leached black soils typical of the analyzed territory, powerful humus, and heavy loamy non-eroded on loess-like clays (Table 2).

Table 2. Average indicators of agroecological characteristics of the arable horizon of leached black soils of upland agrogenically altered lands of the northwestern part of the Penza region.

Agroecosystem	Depth A (A arable + A 1)	$C_{org.}$ (%)	pH_{KCl}	Density (g/cm^3)	The amount of absorbed bases (ppm)	The degree of saturation of the bases (%)
Belozerka	55	7 .8	5 .52	1 .30	36 .5	85 .6
Flat accumulative landscape	54	8 .0	5 .58	1 .28	36 .6	86 .2
Flat denudation landscape	57	7 .6	5 .63	1 .31	36 .7	84 .8

The humus content is stable throughout the surveyed area with slight fluctuations in the range of 8-9%, and a decrease in its content along the profile occurs at a depth of 50-55 cm. The thickness of the humus horizon is 65-69 cm (Morev *et al.* 2024). Good physical and chemical properties characterize soils. The content of mobile nitrogen, phosphorus and potassium forms is uneven and depends on the mesorelief. The boiling depth is from 10% hydrochloric acid, and the appearance of pseudomycelia is noted from 128 cm. The spread of the average values of the compared agroecological characteristics of the site under consideration and similar landscape formations of the study region also does not exceed 5%, which may indicate the typicality and representativeness of the selected research object. To assess carbon stock dynamics during the growing season, a series of measurements of CO_2 fluxes of soil cover on acrogenic and postagrogenic fallow lands of each of the analyzed sites were carried out. The measurements were carried out at 10:00 a.m. for three days in triple repetition, followed by averaging of indicators. The data obtained made it possible to identify the main patterns of CO_2 emissions of fallow soils and agroecosystems in different forms of mesorelief, highlighting the general patterns and the main distinctive features of the analyzed territories. Thus, in the conditions of agroecosystems Fig. 3, the stages of vegetation of crops are traced. Pre-sowing tillage carried out at the end of April destroys weeds that affect the flow of carbon dioxide during the month, which decreases somewhat.

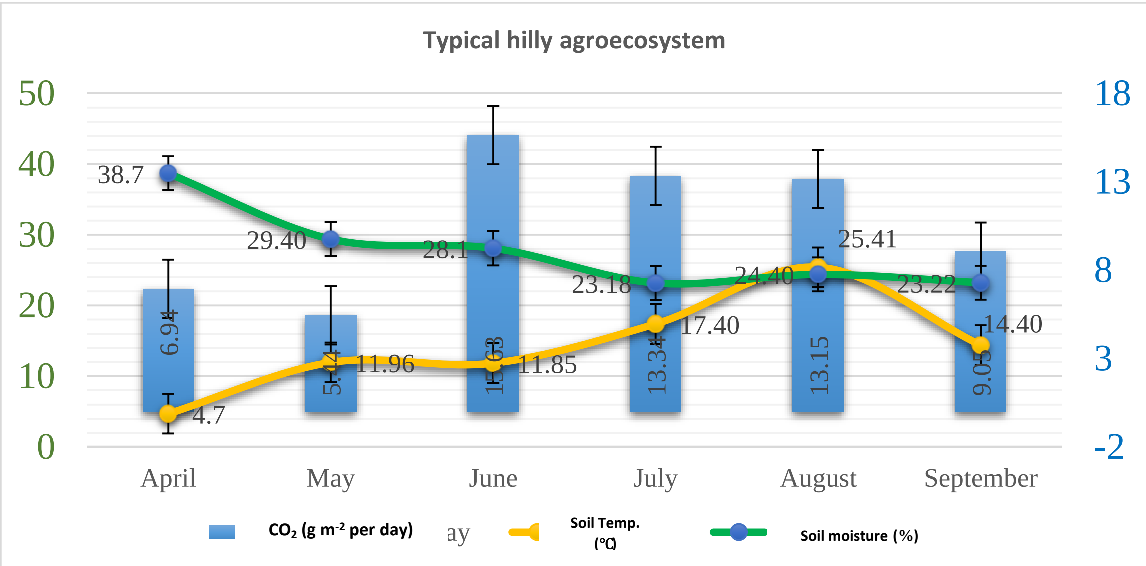

Fig. 3. Dynamics of the CO_2 emission of the typical hilly agroecosystem.

Further sowing of an agricultural crop in late April-early May leads to its maximum vegetation in June, which is highly correlated (K 0.75) with the maximum CO_2 flux simultaneously. Depending on the agricultural crop, its vegetative activity proceeds in different ways. In the typical hilly agroecosystem (Fig. 3), sunflowers were cultivated, with harvesting upon completion of maturation and drying of biomass at the end of September, which is clearly traced by the general trend of CO_2 dynamics. Sugar beet was cultivated on the typical flat agroecosystem, and the trend of its development, traced by soil respiration, differed somewhat from sunflower both by a lower growth rate in June and by the duration of vegetation associated with harvesting the crop at maturity from mid-October. Accordingly, the flow of carbon dioxide in the graph (Fig. 4) naturally increases with the acceleration of the growing process and the active set of sugars by the end of September.

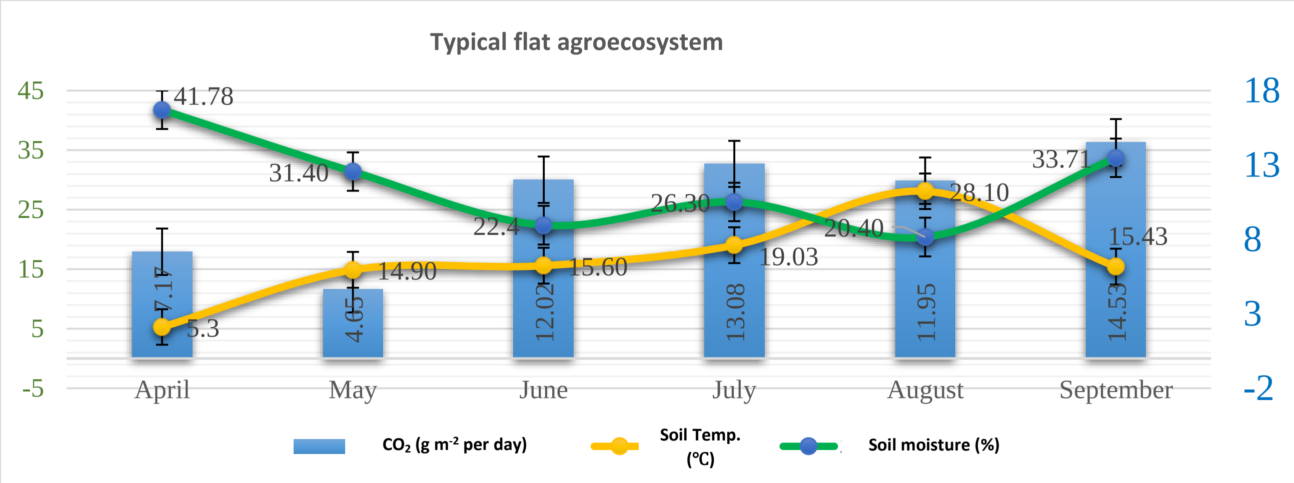

Fig. 4. Dynamics of the CO_2 emission of the typical flat agroecosystem

The spring dynamics of the CO_2 flux in April and May, before the start of active crop vegetation, are statistically homogeneous, considering calculation errors. The dynamics of carbon dioxide emissions from fallow lands also correspond to the nature of the vegetation period of cover in the analyzed territory (Buzylev *et al.* 2024). Thus, the hydromorphic typical hilly deposit's vegetation cover is characterized by two growth stages corresponding to the activity of spring meadow plants and their summer followers. The decline in vegetation activity in wet meadow ecosystems is observed only with the onset of frost (late September – early October), and the graph (Fig. 5) is not displayed.

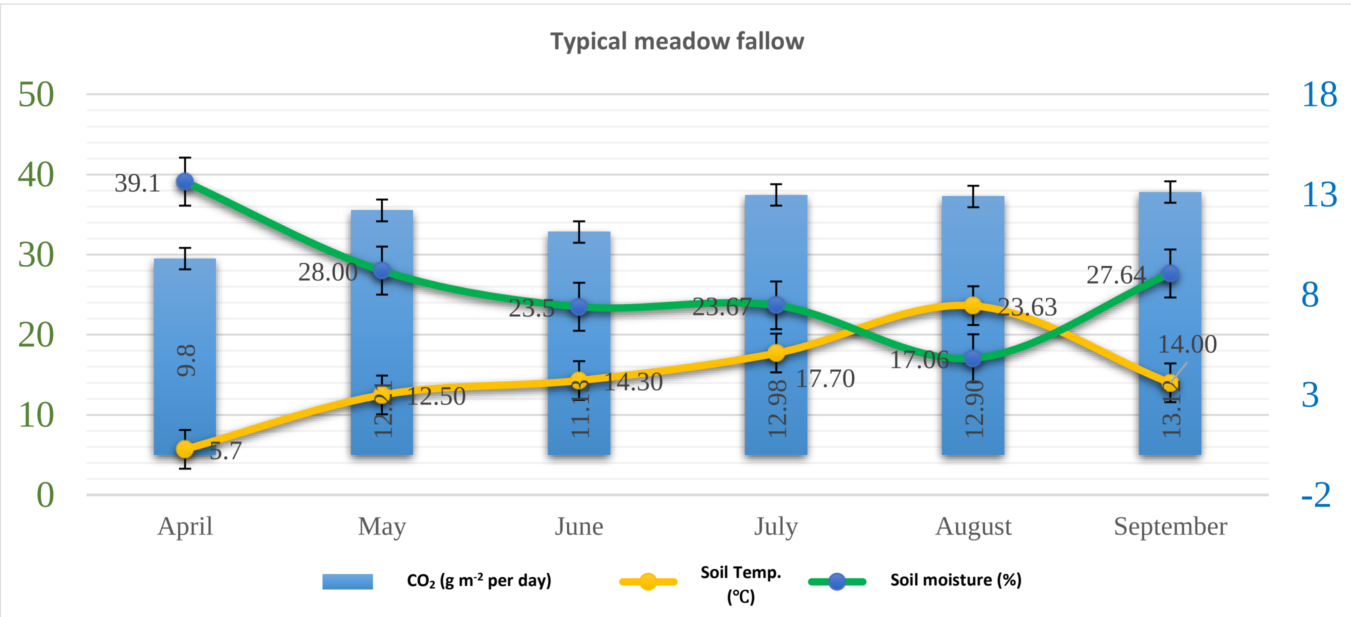

Fig. 5. Dynamics of CO_2 emissions from meadow fallow ecosystems.

Forest ecosystems are characterized by a vegetation period similar to agroecosystems from the beginning of April to the end of September. However, due to the enormous volume of biomass and energy flows involved in tree growth, soil emission graphs (Fig. 6) are more pronounced and smoothed relative to all analyzed types of restored natural and anthropogenic transformed systems. The analysis of CO_2 emission power, soil temperature, and humidity made it possible to assess the mutual influence of the studied factors since everywhere there is an inverse unconditional dependence of the moisture content of the arable soil horizon and its temperature (K -0.89 ± 0.06). The intensity of the CO_2 flux everywhere had the greatest dependence on soil temperature and a high inverse relationship with its humidity. In the two analyzed agroecosystems, the strength of the identified bonds (To 0.81 ± 0.08) was 26-27% higher than in fallow areas. At the same time, the nature of the diversity of the studied parameters showed the greatest variation in soil temperature (V 42%) of the parameters considered in this material. The variation in CO_2 emissions and air temperature did not exceed 26%.

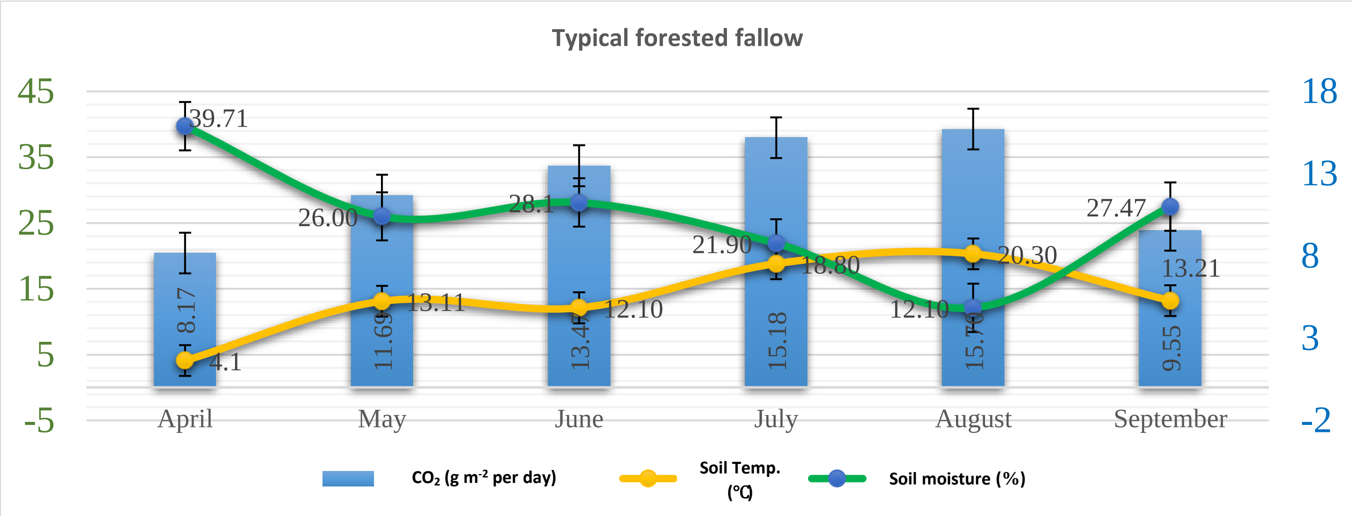

Fig. 6. Dynamics of CO_2 emission of forested fallow soils.

The calculation of the soil carbon reserve in the work was equated to agroecosystems in connection with the purpose of land use and was carried out according to the methodological guidance of the FITZ "Soil Institute named after V.V. Dokuchaev" according to the formula:

$$3\mathrm{C}\ (ton/ha) = \mathrm{C} \times h \times r$$

where C (%) is the carbon content in the soil; h (cm) is the thickness of the humus layer; r (g cm^{-3}) is the density of the soil. Due to highly humanized black soils, the analyzed fallow and agricultural ecosystems have an initial increased soil carbon reserve (Table 3).

Table 3. Summary carbon balance of representative sites in the north-western part of the Penza region.

Ecosystem	Depth (A+AB; cm)	$C_{organic.}$ (%)	The density of the soil composition, (g m^{-3})	Carbon stock (ton ha^{-1})	Emission CO_2 (ton ha^{-1})	Carbon balance, vegetation (ton ha^{-1})	Dynamics of the carbon stock (ton ha^{-1})
Belozerka agroecosystem	69	7 .8	1 .42	443	8 .5	-2	-10 .5
Belozerka deposit	69	8 .9	1 .42	506	13 .32	14 .01	0 .69
Podgornoye agroecosystem	106	6 .7	1 .27	523	9 .95	-0 .08	-10 .03
Podgornoye deposit	80	7 .9	1 .35	495	4 .04	12 .24	8 .2

The minimum reserve is observed in the acrogenic territories of a typical flat ecosystem. It is associated with significant vegetation removal (from 2 ton ha^{-1}) and an average CO_2 emission of 8.5 ton ha^{-1}. The typical hilly agroecosystem, characterized by accumulative meadow-black soils, the presence of alluvial zones from sloping lands, and an increased thickness of the humus horizon (up to 106 cm), showed the maximum reserve of soil carbon. The maximum CO_2 emission is observed in the typical flat forest fallow ecosystem. It can be associated with the active development of 30-year-old birch (over 13ton ha^{-1}), compensated by more abundant fall (up to 14 ton ha^{-1}). The minimum soil emission of carbon dioxide was observed on the fallow soils of the typical hilly ecosystem (4 ton ha^{-1}) and, in our opinion, depends on increased soil moisture, and as a result of its reduced microbiological activity. At the same time, the high amount of plant litter of the floodplain meadow agroecosystem (over 12 ton ha^{-1}) makes it possible to show the maximum positive balance of soil carbon stock (over 8 ton ha^{-1}). Representative agroecosystems of the analyzed territories showed statistically homogeneous high CO_2 emissions with a negative carbon vegetation balance, directly dependent on the cultivated crop, with a total exceptionally negative carbon stock dynamics exceeding 10 ton ha^{-1} per year. Thus, our study supports that soil carbon stocks are higher in areas with woody plants. However, inappropriate afforestation of existing species-rich grassland habitats may undermine their biodiversity.

CONCLUSION

The obtained data on the carbon stock in the representative fallow lands of the Penza region show positive dynamics characteristic of natural ecosystems. Raising fallow soils and transferring them to arable lands will significantly decrease carbon reserves due to increased soil and vegetation emissions and require the development of special measures to minimize the negative environmental impact. Proper land use and management can increase the carbon storage potential of soil contents. Improvements in crop cultivation technologies can be compensatory measures based on introducing organic farming systems in combination with numerous existing systems that reproduce and preserve the original soil fertility.

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