

Calculation of Carbon Sequestration in Soil Based on Actual Crop Yield and Soil-Climatic Conditions

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The concept of carbon sequestration is widely misunderstood, leading to misleading conclusions that are reflected in unrealistic climate change mitigation strategies. Most studies presented as carbon sequestration do not understand the term carbon sequestration in accordance with the IPCC definition. Most often, carbon sequestration is equated with carbon stocks or carbon balance. As a result, carbon sequestration models continue to be developed worldwide that have little in common with sequestration. Our methodology for calculating carbon sequestration is based on a definition grounded in the actual removal of CO₂ from the atmosphere by plants and its retention in the soil. The input data include real values for the quantity and quality of incoming biomass in relation to the plant, as well as real data on the main factors determining the geographical distribution of carbon on Earth in relation to the soil, such as temperature, precipitation, and clay content. Testing of the methodology on real field plots in practice has shown that the results are compatible with global sequestration prediction models or closely approximate them. Simultaneously, a scale for assessing carbon sequestration was developed, which is still absent in existing models. The methodology will be part of the digital advisory platform AgroAssistent, which will serve common farming practice within Slovakia.

Keywords: carbon sequestration, climate, methodology, plant, soil

1 Introduction

Soil is the largest terrestrial carbon reservoir and plays a key role in its global cycle, thereby influencing climate processes (Lal, 2004; Georgiou et al., 2022). Don et al. (2023) draw attention to the incorrect use of technical terms in the context of climate change mitigation, which can lead to unintended consequences and an overestimation of the role of carbon in the soil. An analysis of 100 recent international publications about carbon sequestration in the soil revealed that the vast majority of authors used the term incorrectly or ambiguously. The correct use of the terms “carbon sequestration”, “negative emission”, “climate change mitigation” and “soil carbon accumulation” is important for improving communication among stakeholders across science, policy, industry and society. For example, only 4% of studies use the term carbon sequestration correctly (Don et al., 2023). Increasing soil carbon accumulation can

compensate for greenhouse gas emissions. However, this increase can only be considered for carbon sequestration in the soil if the global soil carbon stock increases. In soils that lose carbon, measures to increase carbon content in the soil only reduce carbon losses and therefore cannot contribute to removing it from the atmosphere. However, mitigating carbon losses is essential to protect soil and maintain the ecosystem services that soil provides. Increases in carbon stocks (carbon increments) outside the atmosphere can contribute to carbon sequestration and climate change mitigation. However, the existence of carbon (carbon stocks) in soil alone does not contribute to this (Don et al., 2023). Carbon sequestration is the process of transferring carbon from the atmosphere to the soil by plants and other organisms, where it is retained as organic carbon, thereby increasing global soil carbon stocks (IPCC, 2001). Olson et al. (2014) emphasised that this is stored carbon (millennia) and is not immediately

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transformed and released into the atmosphere. Carbon sequestration is therefore not only the process of removing CO₂ from the atmosphere, expressed as the mass of C per area (tC·ha⁻¹), but also per unit of time (tC·ha⁻¹·year⁻¹), since carbon sequestration is always a C flux in connection with a unit of time (Don et al., 2023).

Intensive agricultural use and land-use changes have resulted in a significant loss of soil organic carbon in recent centuries, which importantly contributes to the increase in atmospheric CO₂ concentration. Restoring soil carbon stocks through sequestration is therefore considered to be one of the potential strategies for climate change mitigation and a tool for improving soil fertility (Lal, 2004a). Soils have significant potential for carbon sequestration, with global estimates suggesting they can restore a substantial portion of the carbon lost to intensive agricultural use. For example, Lal (2004) reported that soils affected by long-term use, particularly agricultural soils, have the capacity to bind 50–66% of the carbon lost due to their management, whereby the introduction and optimisation of suitable agrotechnical practices could lead to the sequestration of 0.4–1.2 Gt C per year. This means 0.083–0.250 tC·ha⁻¹·year⁻¹ on agricultural lands and 0.250–0.750 tC·ha⁻¹·year⁻¹ on arable lands worldwide. Paustian et al. (2019) in their study pointed out a higher theoretical potential for carbon sequestration when using standard agronomic conservation practices at the level 2–5 Gt CO₂ per year (0.5–1.36 Gt C per year), while with the large-scale implementation of advanced technologies (such as biochar application, permanent grass crops, deep-rooted crops) this potential can reach up to 8 Gt CO₂ per year (2 Gt C per year). This means that, when applying standard methods, this amounts to 0.104–0.283 tC·ha⁻¹·year⁻¹ on agricultural land and 0.313–0.850 tC·ha⁻¹·year⁻¹ on arable land worldwide. When applying advanced land management practices, this can be 0.417 tC·ha⁻¹·year⁻¹ on agricultural lands and up to 1.250 tC·ha⁻¹·year⁻¹ on arable land. Soil organic carbon clearly has a positive impact on soil fertility; however, its impact on the yield of cultivated crops is secondary and significantly depends on specific soil-climatic conditions. Ma et al. (2023), in their meta-analysis, which included more than 13 thousand experiments from all over the world, pointed out a relatively low response of crops to increases in organic carbon content, while the global increase in the production of major cereals (wheat, corn, rice) was estimated at 0.7%. Simultaneously, it was found that the effect of carbon sequestration on cereal yields is significantly lower than that of nitrogen fertilisation. Another important aspect is the occurrence of soil carbon saturation, with the maximum capacity for soil organic carbon determined by the soil's physicochemical properties, primarily the proportion of fine-grained

fractions (clay content) and mineral associations (Georgiou et al., 2025). Clay is an important stabilising element that plays a dominant role in stabilising carbon in the soil (Das et al., 2023). The relationship between soil organic carbon content and crop yield is not linear but reaches a saturation level, beyond which further increases in soil organic carbon have only a minimal or insignificant effect on production (Ma et al., 2023). Despite the importance of soil as a reservoir, it is important to emphasise that the sequestration process itself does not begin in the soil but in plants through photosynthesis. The fixation of atmospheric CO₂ leads to the formation of plant biomass, which is the primary source of organic carbon entering the soil system (Paustian et al., 2019; Jansson et al., 2021). Plant biomass is the main source of carbon entering the soil system through above-ground residues, root biomass and rhizodeposition (Paustian et al., 2019). These inputs are subsequently transformed by soil microorganisms and participate in the formation of individual fractions of soil organic carbon. The quantity and quality of soil organic carbon are determined by the quantity and quality of plant residues (Jurčová & Torma, 1998). Both root biomass and root exudates are significant sources of carbon input to the soil. Current knowledge indicates that carbon originating from roots is often stabilised in the soil more effectively than carbon from above-ground residues, primarily because it enters the soil matrix directly and is processed by microorganisms (Rasse et al. 2005). Root exudates also represent a rapid transfer of carbon from photosynthesis to the soil, whereby an important part of the products of photosynthesis can be released into the rhizosphere within hours to days and subsequently utilised by microorganisms (Kaiser et al., 2015). These processes play a key role in the formation and transformation of soil organic carbon, as microbial products derived from the processing of plant inputs are the main precursors of stable forms of soil organic carbon (Cotrufo et al., 2013). Several companies have developed calculators for carbon sequestration, but none of them takes into account the combination of the actual achieved biomass yield relative to the yield of the main agricultural product and the chemical composition of crop residues, without considering the remaining carbon in the soil after a year. Moreover, none of them calculates carbon sequestration for a specific field plot with a real clay content, as a basic stabilising element in a region characterised by real annual precipitation and average annual temperature. The company WardKarlson Consulting offers the Biological Carbon Sequestration Calculator, which calculates the carbon the soil absorbs and retains per year and uses input data such as habitat type and area in hectares (WKC GROUP, 2024). Interdisciplinary Science and Public Health has

developed the Carbon Sequestration Potential Calculator, designed in accordance with the IPCC methodology to determine annual carbon storage potential. It estimates the average carbon storage capacity ($\text{tCO}_2\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$). It uses input data on land-use type (forest, meadow, arable land) and also accounts for the geographical region (ISPH, 2021). However, many calculators included under carbon sequestration offer calculations of its balance (ICTA, 2024; CIAT & WLE – Soil Organic Carbon App) or of emissions (FAO, 2011), but not of carbon sequestration itself. Their output is therefore only potential, prediction or emissions. However, none of them yet calculates the actual carbon sequestered in a given year.

Although the process of carbon sequestration in soil is conceptually relatively well described, its practical quantification under conditions of primary agricultural production remains problematic. In practice, different approaches are used, either based on direct measurement of soil organic carbon stocks and their changes or on the estimation and modelling of soil carbon stocks. Modelling is an approach that requires extensive input data and calibration of the models used. From a mechanisms perspective, it is clear that carbon sequestration in soil is directly linked to the amount of carbon entering the soil via plant biomass. This is largely determined by the yields of cultivated crops, which are not only a production parameter but also an indicator of carbon binding through photosynthesis and its potential return to the soil. There is therefore a direct relationship between yield, biomass production and the amount of carbon entering the soil. However, this input is not uniform because the created biomass also has a specific chemical composition. In particular, lignin, as a more stable component of organic matter, plays an important role in long-term carbon storage in the soil. On this basis, a methodological procedure for calculating carbon sequestration in the soil was proposed, using yield as the primary input. In the calculation, the yield is transformed into the individual components of plant biomass (main product, by-product, and root biomass), then into the amount of bound CO_2 , and finally into the carbon entering the soil. The procedure also takes into account the quality of plant residues, especially lignin content and its decomposition, which determine what part of the carbon is actually stabilised in the soil. This approach allows linking the actual yield of cultivated crops to an estimate of the amount of carbon that can be sequestered in the soil. Consequently, this principle is applied to a specific plot in a given region, using the relevant total annual precipitation, average annual temperature, and the proportion of the clay fraction.

2 Methodological Foundation

From the above context, it is evident that carbon sequestration in soil is the process of transforming atmospheric CO_2 fixed by photosynthesis into plant biomass, which is subsequently stored in soil organic matter (as soil organic carbon). This process is determined by the amount of plant phytomass produced and its chemical composition, especially the content of stable fractions such as lignin. The basic assumptions for creating a model of carbon sequestration in soil are:

- overall higher yield is the result of higher biomass production, and thus also higher carbon input into the soil;
- carbon stabilisation depends on the quality of the biomass itself (lignin content);
- the decomposition of organic matter in the soil proceeds according to the kinetics of 1st order (Van Veen & Paul, 1981; McGill & Paul, 2007);
- clay is one of the most important stabilising elements of several mechanisms of carbon stabilisation in the soil (Das et al., 2023);
- precipitation and temperature are limiting factors of all transformation processes in the soil (Zhang et al., 2022).

The methodology was applied to the following choice crops: spring wheat, winter wheat, spring barley, winter barley, corn for grain, corn for silage, and oilseed rape.

2.1 Input Data

2.1.1 Yield and Biomass Production

For each crop, it is necessary to define:

- main product yield ($\text{t}\cdot\text{ha}^{-1}$);
- by-product yield ($\text{t}\cdot\text{ha}^{-1}$);
- root yield ($\text{t}\cdot\text{ha}^{-1}$).

It is based on the cultivated yield. The yield is usually expressed in $\text{t}\cdot\text{ha}^{-1}$ and varies widely depending on soil and climatic conditions and the year. The yield can be defined and understood from different perspectives; however, in this case, it is calculated separately as the yields of the main product and the by-product. The yield of the main product represents the economic yield, so the part of the plant for which it is primarily cultivated (cereals primarily for grain, corn for silage primarily for above-ground biomass). The yield of by-products includes above-ground plant parts that arise simultaneously with the main product during the growth and harvesting process but are not a primary aim of cultivation (cereals are secondary for straw). The yield of the by-product is determined in accordance with Section 13 of Decree 151/2016 Coll., based on the ratio of the main product to the by-product. For example, in the case of cereals – amount of grain to amount of straw 1 : 1; in the case of corn – amount of grain to amount of

stover 1 : 1.6; in the case of oilseed rape – amount of seed to amount of straw is 1 : 2.6. The ratios of post-harvest above-ground and root residues are given by Torma and Vilček (2017). Root residues (roots) are residues in the soil after harvesting the main product and by-product. Due to the relatively limited information about the ratios between the weight of the main product and the weight of roots and the greater amount of information about the ratio of the weights of above-ground/below-ground phytomass, the calculation of root weights is carried out by counting the weight of the main product (grain) and the weight of above-ground vegetative mass and calculating the weight of roots is counted from the above-ground/below-ground phytomass ratio. For this purpose, the above-ground/below-ground phytomass ratios determined by Jurčová and Torma (1998) are used. For the calculation of the above-ground biomass and root ratio, the ratio was used for winter wheat, winter barley, spring barley, corn for grain, corn for silage 4.81 : 1; for spring wheat 3.69 : 1; for oilseed rape 4.35 : 1. The total calculation of post-harvest residues that remain on the field after the harvest of the yield of main product is calculated according to the equation (1):

$$CR_{tot} = CR_{ab} + CR_{be} \quad (1)$$

where: CR_{tot} – the total yield of post-harvest residues ($t \cdot ha^{-1}$); CR_{ab} – the yield of above-ground biomass ($t \cdot ha^{-1}$); CR_{be} – the yield of below-ground biomass (root residues) ($t \cdot ha^{-1}$)

In the case of the main agricultural product (grain/seed) leaving the field, the main under-ground phytomass (straw/stover) and root residues remain. In the case of corn for silage, only root residues are counted.

2.1.2 CO₂ Consumption for the Creation of Phytomass of Cultivated Crops

The calculation of CO₂ consumption to creation of 1 kg of dry matter ($Cons_{CO_2/kg}$) is as follows (2):

$$Cons_{CO_2/kg} = 3.7 \times C \text{ in dry matter of plants} \quad (2)$$

From the data of several authors (Watanabe 1976; Nátr 2006), it follows that when calculating the CO₂ needs to create dry matter of cereals or grains (wheat, barley, corn), but also of vegetative matter (plants in which tissue of the generative and vegetative organs the saccharides are dominated), it will be calculate so that to create 1 gram of seed (100% dry matter), the mentioned plants must bind 1.64 g of CO₂ (the percentage of carbon in starch is 44.4%) (3).

$$Cons_{CO_2/kg} = 3.7 \times 0.444 = 1.64 \text{ kg CO}_2 \text{ kg dry matter} \quad (3)$$

CO₂ contains only 27.3% C, so 1 g C requires 3.7 g CO₂ ($44/12 = 3.7$).

In plants such as oilseed rape, producing 1 g of seed requires up to 2.831 g of CO₂ (the C content of oleic acid is 76.5%) (4).

$$Cons_{CO_2/kg} = 3.7 \times 0.765 = 2.831 \text{ kg CO}_2 \text{ kg dry matter} \quad (4)$$

Since there are no differences among the carbon contents in the vegetative parts (cereals, oilseed), one common value is calculated, which represents the intake of 1.64 kg of CO₂ for the production of 1 kg of dry matter of the vegetative parts of winter wheat, spring wheat, winter barley, spring barley, corn for grain and silage and of 2.831 kg of CO₂ for oilseed rape.

2.1.3 Ratio of Above-Ground and Root Post-Harvest Residues

Each plant species has its own specific morphology, which is reflected in the heterogeneity of quantitative indicators of plant residues, including the differences between winter and spring forms. Another important factor is the technology of their cultivation: the difference lies in whether cereal straw is incorporated into the soil and whether the corn is cultivated for grain or for silage. This is also reflected in the resulting ratio of above-ground to root mass of post-harvest residues entering the soil after the main agricultural product is harvested. These ratios were determined experimentally, and their percentage proportions were published by Bielek and Jurčová (2010). For the purpose of calculating the number of inputs, the percentage proportions of above-ground and root mass are given (Table 1).

2.1.4 Lignin Content in Post-Harvest Residues of Cultivated Crops and the Calculation of Real Lignin Inputs in the Form of Post-Harvest Residues Into the Soil

The stability of soil organic carbon is a key determinant of its storage in soil (Ma et al., 2018). The chemical composition of plant residues thus directly influences carbon sequestration (Cotrufo et al., 2013), especially the proportion of lignin in plant residues, as the most stable carbon component (Chen et al., 2024), which remains in the soil even after a year of incorporation of plant residues into the soil (Bahri et al., 2006; Liu et al., 2025) and is a key component in carbon sequestration (Chen et al., 2025). CO₂ production is thus related to the lignin content in the plant residues (Yanni et al., 2011). Above-ground plant residues have a lower lignin content than root residues, so root residues, in particular, support long-term carbon sequestration (Puget & Drinkwater, 2001). Since lignin has different proportions in the above-

Table 1 The average amounts of dry matter of plant residues at a given yield of the main product

Crop	Yield of above-ground residues (t·ha ⁻¹)	Proportion of above-ground residues (%)	Yield of root residues (t·ha ⁻¹)	Proportion of root residues (%)
Spring wheat	4.98	65.10	2.67	34.90
Winter wheat	6.54	70.40	2.75	29.60
Spring barley	4.19	70.18	1.78	29.82
Winter barley	4.71	69.57	2.06	30.47
Corn for grain	7.04	75.37	2.30	24.62
Corn for silage	1.36	29.12	3.31	70.88
Oilseed rape	8.42	75.20	2.70	24.80

Source: Bielek & Jurčová, 2010

ground and root mass, it is necessary to determine its content separately for each part (Beloserski et al., 1956). The real lignin inputs, in percentages, from specific plant residues were subsequently calculated as the sum of the percentages of their inputs from the above-ground and root mass (Table 2).

Real lignin inputs (Lig_{CR}) are calculated from their contents in above-ground and root residues and their mutual ratios at which they enter the soil (5).

$$Lig_{CR} = \frac{Lig_{ab} \times CR_{ab}}{100} + \frac{Lig_{be} \times CR_{be}}{100} \quad (5)$$

where: Lig_{ab} – the lignin content of the above-ground residues (%); CR_{ab} – the proportion of the above-ground yield (%); Lig_{be} – the lignin content of the below-ground root residues (%); CR_{be} – the proportion of the below-ground root yield (%)

2.1.5 Dynamics of Lignin Decomposition (Lignin Rest after 1 Year in the Soil)

The reaction rate is directly proportional to the concentration of substrate. The validity of 1st-order kinetics for the decomposition of organic substances is experimentally established. Such a reaction proceeds according to the following equation (6):

$$[A]_t = [A]_0 \times e^{-kt} \quad (6)$$

In this way, it is possible to express the decomposition of each fraction of organic matter entering the soil using 1st-order kinetics. Plant residues decompose in the soil according to 1st-order kinetics (e^{-kt}) (Molina et al., 1983; Van Veen & Paul, 1981). The decomposition of lignin in the soil proceeds in the same way (Van Veen & Paul, 1981). The lignin content (A_{t-lig}) is calculated for the relevant lignin content entering into the soil through the post-harvest residues of the relevant crop, and in a time interval of 1 year (7):

$$A_{t-lig} = A_0 \times e^{-kt} \quad (7)$$

where: k – the rate constant of decomposition of the stable lignin component (0.01 day⁻¹); t – the time in days (365 days)

After substitution, the equation has the form (8):

$$A_{t-lig} = A_t \times e^{-0.01 \times 365} \\ A_{t-lig} = A_t \times 0.026 \quad (8)$$

where: A_{t-lig} – the proportion of lignin in % that remains in the soil after 1 year of incorporation of plant residues into the soil; A_t – the proportion of lignin in % that enters the soil at the time of their incorporation; 0.01 – the rate constant for lignin (days⁻¹); 365 – the number of days in a normal year

Table 2 Proportion of lignin in the absolute dry matter of above-ground and root plant residues in unashed mass

Crop	Lignin in the above-ground residues (%)	Lignin in the root residues (%)
Spring wheat	30.36	47.12
Winter wheat	31.76	39.98
Spring barley	25.70	40.83
Winter barley	11.99	29.10
Corn for grain	14.71	26.14
Corn for silage	14.71	26.14
Oilseed rape	27.22	34.69

The equation is thus valid for all crops. The different values for each crop are only the A_t values; thus, the actual lignin content entering the soil at 0 days (when the residues are incorporated).

2.1.6 Calculation of Bound CO_2 in the Phytomass of Cultivated Crops

The total bound CO_2 in the phytomass of cultivated crops (CR_{CO_2}) in $\text{t}\cdot\text{ha}^{-1}$ was calculated based on equation (9):

$$CR_{\text{CO}_2} = CR_{\text{tot}} + \text{Cons}_{\text{CO}_2/\text{kg}} \quad (9)$$

where: CR_{CO_2} – the total yield of post-harvest residues ($\text{t}\cdot\text{ha}^{-1}$); $\text{Cons}_{\text{CO}_2/\text{kg}}$ – the CO_2 consumption to create 1 kg of dry matter

The volume of the total bound CO_2 in the phytomass of cultivated crops will thus be the product of the yield of the residues of the relevant crop and the calculated coefficient of CO_2 consumption to create 1 kg of dry matter, so for cereals 1.64 g CO_2 per 1 g of 100% grain dry matter and 2.831 g CO_2 for 1 g of 100% seed dry matter.

2.1.7 Calculation of Sequestered Carbon in Soil

The total amount of carbon stored/sequestered in the soil (C_{seq}) is calculated according to equation (10):

$$C_{\text{seq}} = C_{\text{CR}} \times 1,000 \times A_{t-\text{lig}}/100 \quad (10)$$

where: C_{CR} – the carbon bound in post-harvest residues obtained by calculation from CO_2 bound in post-harvest residues through its molecular weight $C = \text{CO}_2 \times 0.2727$; 1,000 – the conversion (kg); $A_{t-\text{lig}}$ – the proportion of lignin in % that remains in the soil after 1 year of incorporation of plant residues into the soil; 100 – the conversion from percentages

Lignin decomposition does not have a linear character, as in the early stages, its decomposition rate is higher due to co-metabolism (Hall et al., 2020; Chen et al., 2024), but it is still so stable that a significant amount remains in the soil even after a year of incorporating plant residues. Bahri et al. (2006) report that after a year, there is still 56–71% lignin in the soil. The dynamics of lignin decomposition from corn residues were monitored on arable land for up to 9 years. Dignac et al. (2005) also reported that after 9 years, only 47% of the lignin had mineralised. The lignin turnover in topsoil after the conversion of the grassland ecosystem was 5–23 years, and in the topsoil of cultivated land, 9–38 years. A significant proportion of lignin in soils of temperate regions can be stabilised for up to several decades (Heim & Schmid, 2006). The increase in carbon

sequestration is thus associated with the presence of lignin (Tang et al., 2024). Barančíková et al. (2013) report a potential for soil organic carbon sequestration of 10–140 $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ (< 0.2 m), and with increased carbon inputs (more intensive scenarios), this potential reaches up to 110–490 $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ (< 0.3 m) (Koco et al., 2022). The presented values represent the sequestration potential modelled using the RothC model to a depth of 0.2 or 0.3 m, respectively. The presented scenarios are getting significantly closer to the real values calculated by our methodology.

For the application under real conditions, the given amount of carbon C_{seq} is converted using the clay content of a particular plot and the climatic parameters of a particular region. The clay content is incorporated through Hassink's (1997) equation (11) of linear regression for the capacity of saturation of organic carbon by particles up to < 20 μm (in LPIS SR as clay values):

$$y = 0.37 \times x + 4.09 \quad (11)$$

where: x – the content of particles < 20 μm

Temperature and precipitation are incorporated into the model as MT index (12):

$$MT = T \frac{M}{12} \times \frac{1}{3} \times \frac{1}{1,000} \quad (12)$$

where: T – the average annual temperature ($^{\circ}\text{C}$); M – the total annual precipitation (mm); $1/3$ – the reduction for evapotranspiration; 1,000 – the unit conversion; 12 – the number of months

The methodology does not calculate the carbon stored in soil over centuries to millennia, as defined by the IPCC. The calculated value represents an estimate of the annual amount of carbon with the potential for long-term stabilisation in the soil, based on the actual yield achieved, the quality of plant residues, the clay content, and the climatic conditions of the specific locality. Concept saturation of soil carbon indicates the limit of accumulation of organic carbon in the whole soil, which is determined by the internal physicochemical properties of carbon stabilisation groups: unprotected, physically protected, chemically protected, and biochemically protected.

2.2 Evaluation of the Amount of Carbon Sequestered in the Soil

The evaluation of carbon sequestration (Table 3) was carried out on the amount of sequestered carbon in $\text{kg}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$. The values for the amount of sequestered carbon calculated by our proposed methodology

correspond to those reported in the studies by Rothamsted Research (Poulton et al., 2017) and EPJ SOIL (Don et al., 2023). The results confirm that the values of the “four part per 1,000 (4P1000)” initiative are only partially achievable, which is the concept that strictly defines that an annual global increase of organic stocks in the soil by 0.4% (4‰) in the first 0.3 to 0.4 m of the soil profile can compensate for global anthropogenic greenhouse gas emissions and at the same time increase agricultural productivity.

Table 3 Carbon sequestration levels for selected crops and soils in regions of Slovakia

Sequestered amount of C (kg·ha ⁻¹ ·year ⁻¹)	Evaluation
< 60	extremely low
60–135	very low
136–210	low
211–285	medium
286–355	high
356–450	very high
> 450	extremely high

4 Conclusions

The results obtained from real current data are consistent with, or close to, global carbon sequestration prediction models. In the climatic region with an average annual temperature of 10.4 °C, an annual precipitation of 589 mm, a soil clay content of 35%, and an oilseed rape yield of 4 t·ha⁻¹, approximately 232 kg C·ha⁻¹·year⁻¹ will be sequestered in the soil. Carbon sequestration is significantly higher for winter cereals with straw left in the field than for spring cereals, and likewise for grain corn with stover left in the field compared to corn for silage. The methodology was tested on real data, which includes actual yields, temperature, precipitation, and is linked to the soil data from the Land Parcel Identification System (LPIS).

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Erika Balontayová: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology,

Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. Vladimír Šimanský: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

AI and AI-Assisted Technologies use Declaration

The following AI-assisted tool was used during the preparation of the manuscript: Grammarly (AI-assisted tool used for language refinement and formatting alignment with the journal guidelines). The authors take full responsibility for the content of the article.

References

- Bahri, H., Dignac, M. F., Rumpel, C., Rasse, D. P., Chenu, C., & Mariotti, A. (2006). Lignin turnover kinetics in an agricultural soil is monomer specific. *Soil Biology and Biochemistry*, 38(7), 1977–1988. <https://doi.org/10.1016/j.soilbio.2006.01.003>
- Barančíková, G., Makovníková, J., Skalský, R., Tarasovičová, Z., Nováková, M., Halás, J., Koco, Š., & Gutteková, M. (2013). Changes in organic carbon pool in agricultural soils and its different development in individual agro-climatic regions of Slovakia. *Agriculture (Poľnohospodárstvo)*, 59(1), 9–20. <https://doi.org/10.2478/agri-2013-0002>
- Beloserski, A. N., Proskurjakow, N. I., & Oparin, A. I. (1956). *Praktikum der Biochemie der Pflanzen*. [Practical Course in Plant Biochemistry]. VEB Deutscher Verlag der Wissenschaften.
- Bielek, P., & Jurčová, O. (2010). *Metodika bilancie pôdnej organickej hmoty a stanovenia potreby organickeho hnojenia poľnohospodárskych pôd*. [Methodology for Soil Organic Matter Balance and Determination of Organic Fertilization Needs of Agricultural Soils]. VUPOP.
- Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Deneff, K., & Paul, E. (2013). The microbial efficiency-matrix stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Global Change Biology*, 19, 988–995. <https://doi.org/10.1111/gcb.12113>
- Das, A., Purakayastha, T. J., Ahmed, N., Das, R., Biswas, S., Shivay, Y. S., Sehgal, V. K., Rani, K., Trivedi, A., Tigga, P., Sahoo, J., Chakraborty, R., & Sen, S. (2023). Influence of clay mineralogy on soil organic carbon stabilization under tropical climate, India. *Journal of Soil Science and Plant Nutrition*, 23, 1003–1018. <https://doi.org/10.1007/s42729-022-01099-x>
- Dignac, M. F., Bahri, H., Rumpel, C., Rasse, D. P., Bardoux, G., Balesdent, J., Girardin, C., Chenu, C., & Mariotti, A. (2005). Carbon-13 natural abundance as a tool to study the dynamics of lignin monomers in soil: an appraisal at the Cloiseau experimental field (France). *Geoderma*, 128, 3–17. <https://doi.org/10.1016/j.geoderma.2004.12.022>
- Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., Emde, D., Seitz, D., & Chenu, C. (2023). Carbon sequestration in soils and climate change mitigation – Definitions and pitfalls. *Global Change Biology*, 30, e16983. <https://doi.org/10.1111/gcb.16983>

- Food and Agriculture Organization of the United Nations. (2011). *EX-Ante Carbon-balance Tool (EX-ACT): Technical guidelines for version 4*. https://www.fao.org/fileadmin/templates/ex_act/pdf/Technical_guidelines/EX-ACT-tech-guidelines_V4.pdf
- Georgiou, J. K., Angers, D., Champigny, R. E., Cotrufo, M. F., Craig, M. E., Doetterl, S., Grandy, A. S., Lavallee, J. M., Lin, Y., Lugato, E., Poeplau, Ch., Rocci, K. S., Schweizer, S. A., Six, J., & Wieder, W. R. (2025). Soil carbon saturation: What do we really know? *Global Change Biology*, 31, e70197. <https://doi.org/10.1111/gcb.70197>
- Georgiou, R. K., Jackson, R. B., Vinduškova, O., Abramoff, R. Z., Ahlström, A., Feng, W., Harden, J. W., Pellegrini, A. F. A., Polley, H. W., Soong, J. L., Riley, W. J., & Torn, M. S. (2022). Global stocks and capacity of mineral-associated soil organic carbon. *Nature Communications*, 13, 3797. <https://doi.org/10.1038/s41467-022-31540-9>
- Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and particles. *Plant and Soil*, 191, 77–87. <https://doi.org/10.1023/A:1004213929699>
- Hall, S. J., Huang, W., Timokhin, V. I., & Hammel, K. E. (2020). Lignin lags, leads, or limits the decomposition of litter and soil organic carbon. *Ecology*, 101(9), e03113. <https://doi.org/10.1002/ecy.3113>
- Heim, A., & Schmidt, M. W. I. (2006). Lignin turnover in arable soil and grassland analysed with two different labelling approaches. *European Journal of Soil Science*, 58, 599–608. <https://doi.org/10.1111/j.1365-2389.2006.00848.x>
- Chen, X., Ni, X., Zheng, G., Hu, M., & Chen, H. Y. H. (2024). Changes in plant lignin components and microbial necromass matter with subtropical forest restoration. *Geoderma*, 445, 116875. <https://doi.org/10.1016/j.geoderma.2024.116875>
- Chen, Z., Ma, J., Wang, F., Ma, J., Zou, P., Sun, W., Yu, Q., & Wang, Q. (2025). Long-term phosphorus addition enhances the contributions of plant lignin and microbial necromass to soil organic carbon in a rice–wheat rotation. *Applied Soil Ecology*, 209, 106010. <https://doi.org/10.1016/j.apsoil.2025.106010>
- Interdisciplinary Science and Public Health. (2021, June 20). *Carbon sequestration potential calculator – Simplified version*. <https://sciph.info/isph-calculators/carbon-sequestration-potential-calculator/>
- Intergovernmental Panel on Climate Change. (2001). Annex B: Glossary of terms. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, & K. S. White (Eds.), *Climate change 2001: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 979–995). Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/03/WGII_TAR_full_report-2.pdf
- International Center for Tropical Agriculture. (2021). *Soil Organic Carbon App*. CGIAR Research Program on Water, Land and Ecosystems. <https://archive.iwmi.org/wle/solutions/soil-organic-carbon-app/>
- Jansson, C., Faiola, C., Wingler, A., Zhu, X-G., Kravchenko, A., de Graaff, M-A., Ogden, A. J., Handakumbura, P. P., Werner, C., & Beckles, D. M. (2021). Crops for carbon farming. *Frontiers in Plant Sciences*, 12, 636709. <https://doi.org/10.3389/fpls.2021.636709>
- Jurčová, O., & Torma, S. (1998). *Metodika Kvantifikácie Živinového Potenciálu Rastlinných Zvyškov*. [Methodology for Quantifying the Nutrient Potential of Plant Residues]. VÚPU.
- Kaiser, Ch., Kilburn, M. R., Clode, P. L., Fuchslueger, L., Koranda, M., Cliff, J. B., Solaiman, Z. M., & Murphy, D. V. (2015). Exploring the transfer of recent plant photosynthates to soil microbes: Mycorrhizal pathway vs. direct root exudation. *New Phytologist*, 205, 1537–1551. <https://doi.org/10.1111/nph.13138>
- Koco, Š., Skalský, R., Barančíková, G., & Bezák, P. (2022). National contribution of Slovakia to the global soil organic carbon sequestration potential map. *Pedosphere Research*, 2(2), 63–73.
- Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, 123(1-2), 1–22. <https://doi.org/10.1016/j.geoderma.2004.01.032>
- Lal, R. (2004a). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304, 1623. <https://doi.org/10.1126/science.1097396>
- Liu, Y., Li, W., Meng, H., Xu, Q., Sun, L., Zhang, L., Ba, Q., Liu, X., Liu, Ch., & Jiang, L. (2025). Contributions of microbial necromass and plant lignin to soil organic carbon stock in a paddy field under simulated conditions of long-term elevated CO₂ and warming. *Soil Biology and Biochemistry*, 201, 109649. <https://doi.org/10.1016/j.soilbio.2024.109649>
- Ma, T., Zhu, S. S., Wang, Z. H., Chen, D. M., Dai, G. H., Feng, B. W., Su, X. Y., Hu, H. F., Li, K. H., Han, W. X., Liang, C., Bai, Y. F., & Feng, X. J. (2018). Divergent accumulation of microbial necromass and plant lignin components in grassland soils. *Nature Communications*, 9, 3480. <https://doi.org/10.1038/s41467-018-05891-1>
- Ma, Y., Woolf, D., Fan, M., Qiao, L., Li, R., & Lehmann, J. (2023). Global crop production increase by soil organic carbon. *Nature Geoscience*, 16, 1159–1165. <https://doi.org/10.1038/s41561-023-01302-3>
- McGill, W. B., & Paul, E. A. (2007). Carbon turnover and dynamics. In E. A. Paul (Ed.), *Soil microbiology, ecology, and biochemistry* (3rd ed.). Academic Press (pp. 349–374).
- Ministerstvo pôdohospodárstva a rozvoja vidieka Slovenskej republiky. (2016). *Vyhľadávka č. 151/2016 Z. z., ktorou sa ustanovujú podrobnosti o agrochemickom skúšaní pôdy a o skladovaní a používaní hnojív*. Slov-Lex. <https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2016/151/>
- Molina, J. A. E., Clap, C. E., Shaffer, M. J., Chichester F. W., & Lasron, W. S. (1983). NCSOIL, a model of nitrogen and carbon transformation in soil: Description, calibration and behavior. *Soil Science Society of American Journal*, 47, 85–91. <https://doi.org/10.2136/sssaj1983.03615995004700010017x>
- Nátr, L. (2006). *Země jako Skleník : Proč Se Bát CO₂?* [Earth as a Greenhouse: Why Be Afraid CO₂?]. Academia edícia Průhledy.
- Olson, K. R., Al-Kaisi, M. M., Lal, R., & Lowery, B. (2014). Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. *Soil Science Society of American Journal*, 78(2), 348–360. <https://doi.org/10.2136/sssaj2013.09.0412>
- Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C Sequestration as a biological negative emission strategy. *Frontiers in Climate*, 1, 8. <https://doi.org/10.3389/fclim.2019.00008>
- Poulton, P., Johnston, J., Macdonald, A., White, R., & Powlson, D. (2017). Major limitations to achieving “4 per 1000” increases in soil organic carbon stock in temperate regions: Evidence

from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology*, 24, 2563–2584.
<https://doi.org/10.1111/gcb.14066>

Puget, P., & Drinkwater, L. E. (2001). Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure. *Soil Science Society of American Journal*, 65, 771–779.
<https://doi.org/10.2136/sssaj2001.653771x>

Rasse, D. P., Rumpel, C. R., & Dignac, M. F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil*, 269, 341–356.

<https://doi.org/10.1007/s11104-004-0907-y>

Tang, Q., Li, W., Dai, W., Wang, J., Zhang, F., Daniell, T. J., Cheng, Y., Wang, S., Yin, W., & Wang, X. (2024). Patterns and determinants of microbial- and plant-derived carbon contributions to soil organic carbon in tea plantation chronosequence. *Plant and Soil*, 505, 811–825. <https://doi.org/10.1007/s11104-024-06712-9>

Torma, S., & Vilček, J. (2017). Rastlinné zvyšky poľnohospodárskych plodín po zbere úrody – zdroj organickej hmoty a živín. [Plant residues of agricultural crops after harvest – a source of organic matter and nutrients]. *Moderná mechanizácia v poľnohospodárstve*, 3, 22–23. <https://www.agroporadenstvo.sk/nove-poznatky-poda?article=982>

Van Veen, J. A., & Paul, E. A. (1981). Organic carbon dynamics in grassland soils. 1. Background information and computer simulation. *Canadian Journal of Soil Science*, 61, 185–201. <https://api.mountainscholar.org/server/api/core/bitstreams/898fa5b2-e3c0-4c6b-81ee-e0249697c73a/content>

Watanabe, I. (1976). Transformation factor from CO₂ net assimilation to dry matter in crop plants. *Japan Agricultural Research Quarterly*, 10(3), 114–118.

WKC Group. (2024, February 16). *Biological carbon sequestration calculator*. <https://www.wkcgroup.com/tools-room/carbon-sequestration-calculator/>

Yanni, S. F., Whalen, J. K., Simpson, M. J., & Janzen, H. H. (2011). Plant lignin and nitrogen contents control carbon dioxide production and nitrogen mineralization in soils incubated with Bt and non-Bt corn residues. *Soil Biology and Biochemistry*, 43, 63–69.
<https://doi.org/10.1016/j.soilbio.2010.09.012>

Zhang, Y., Li, P., Liu, X., Xiao, L., Li, T., & Wang, D. (2022). The response of soil organic carbon to climate and soil texture in China. *Frontiers in Earth Science*, 16(4), 835–845.
<https://doi.org/10.1007/s11707-021-0940-7>