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Carbon recovered in degraded soils under conservation management is highly vulnerable to loss

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Abstract. The recovery of soil organic carbon (SOC) lost due to human activities provides an important opportunity to restore degraded soils and contribute to climate change mitigation. However, there is much debate about how much and for how long carbon can be stored. In this work we took advantage of a long-term experiment established in 1963 in southern Uruguay to evaluate whether integrated crop-pasture systems can recover soil C in a previously degraded site, while also analyzing the persistence of the newly sequestered C. We designed and calibrated compartmental dynamic models that represent the trajectory of soil C and radiocarbon in a soil quality restoration treatment involving the implementation of a crop-pasture rotation following a prolonged period (20 years) of continuous cropping use. We found that it is possible to recover the SOC losses by prolonged agricultural use through the incorporation of perennial pastures in agricultural rotations. Moreover, this recovery occurred at high rates (~ 0.65 Mg ha^{-1} yr^{-1}). However, we found minimal allocation of sequestered SOC to compartments that cycle at low rates and behave as kinetically stable. Instead, most of this new C was incorporated into an intermediate-kinetic-pool that cycles in the order of years to decades. Once management changed (in 2008, after 24 years), this recovered C was susceptible to significant selective loss. The results of this study indicate that, although the compartments associated with greater stability are susceptible to loss over short time scales as a result of agricultural management, their recovery would be a much slower process. The rapid SOC recoveries that can be achieved through conservation management appear to be in forms that are highly susceptible to environmental or management changes.

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1. Introduction

Human activities have led to significant changes in land use (Hu et al., 2020; Klein Goldewijk et al., 2011) that have severely reduced global soil organic carbon (SOC) stocks. The recovery of historically lost SOC is at the center of scientific and policy debates as an important factor contributing to climate change mitigation (Sanderman et al., 2017). The area of land surface used for agriculture has increased from less than 1% at around 1000 AD (Klein Goldewijk et al., 2011) to more than 14.3% in the year 2010 (Hu et al., 2020). Population growth has put increasing pressure on natural resources, resulting in a tripling of global agricultural crop production between 1961 and 2014 (Pellegrini and Fernández, 2018). This increase in global production in recent decades has occurred mainly due to intensification with an increase in harvest yield per unit area, as well as an expansion of land used for cropping in Asia, Africa, and Latin America, with the highest net growth on the American continent (111% increase from 1961 to 2014) (Pellegrini and Fernández, 2018).

Human activities degrade soil physical, chemical and biological properties, negatively impacting soil carbon and water quality. Soil degradation is a threat to food security because it makes agroecosystems increasingly dependent on external inputs to sustain productivity (Kopittke et al., 2019; Lal, 2004). Moreover, SOC changes have important implications for climate change because soil contains about twice as much C as the atmospheric pool (Janowiak et al., 2017; Jobbágy and Jackson, 2000) and small imbalances in the large annual exchanges of C between them can lead to significant short-term shifts in atmospheric CO_2. Sanderman et al. (2017) estimated that 116 Pg of SOC has been lost from the soil (evaluated to two meters depth) because of agricultural activity, and that the rate at which this loss has occurred accelerated sharply over the last 200 years. Another meta-analysis of a large number of previous studies identified an average decrease of 43% in C stock, 42% in N, 27% in P and 33% in S, due to vegetation change from native cover to cropping systems (Kopittke et al., 2017). This same work shows that the application of different types of conservation cropping systems (application of organic amendments, no-till, organic agriculture) can be effective in increasing SOC stocks but cannot completely recover previously lost C (recovering on average around 30% of prior losses).

At the 21st United Nations conference on climate change (COP21) the ‘4 per mille’ initiative emerged, aiming to offset global greenhouse gas (GHG) emissions due to anthropogenic sources through an increase in the SOC stock of 0.4% per year (Minasny et al., 2017). This initiative arose in the framework of efforts to limit the temperature increase to less than 2 °C with respect to pre-industrial values, and the value is derived from the ratio between global human C emissions (8.9×10^{15} g) and a global estimate of SOC stock down to 2 m depth (2400×10^{15} g) (Minasny et al., 2017), suggesting the possibility of an eventual total compensation of GHG emissions with SOC sequestration in the soil. This initiative, despite being aspirational and having little scientific basis in its initial postulation (Baveye and White, 2020), constitutes a framework for collaboration between entities to promote the overall goal of mitigating climate change and improving soil quality (Rumpel et al., 2019).

Initiatives of this nature raise the scientific question of how realistic is soil C sequestration; whether it has the potential to significantly offset GHG emissions, or whether it should simply be seen as a tool to complement other measures such as a decrease in emissions from deforestation or fossil fuel burning (IPCC, 2022). A fundamental question raised in several previous works (Heckman et al., 2022; Lu et al., 2013; Rocci et al., 2021; Schmidt et al., 2011) that has not yet been definitively answered is how fast SOC responds to changes in land management and climate, particularly, how fast SOC can be recovered from previous losses. Soil C sequestration refers to the transfer of C from the atmosphere to the soil for a certain period of time (Muñoz et al., 2024) and, therefore, its storage in compartments of high persistence implies a more intense or efficient sequestration process, avoiding its near-term return to the atmosphere (Lal, 2004; Muñoz et al., 2024). There are numerous management strategies to sequester atmospheric C in agricultural soils, including reducing tillage intensity and incorporating no-tillage, increasing productivity and C input to the system through residues and cover crops, increasing crop diversity and rotations with pastures (Davis et al., 2012; Ogle et al., 2012; Pravia et al., 2019; Rui et al., 2022). In a recent article, González-Sosa et al. (2024) proposed, based on 60 years of data from a long-term experiment (LTE) in Uruguay, that the effect of integrated crop-pasture systems is to preserve the old SOC that was already stored in the soil, when comparing this type of system with an intensive cropping system. However, no information has yet been generated on the capacity of integrated crop-pasture systems to recover C in a soil that was previously managed in intensive agriculture, and on the stability of this new C in the face of new environmental changes, whether due to climate or agronomic management.

In order to describe the ability of integrated crop-pasture systems to recover SOC content in previously degraded soils, it is extremely useful to have time series of SOC data from LTEs in which a management switch from high intensity agriculture to conservation agriculture has been carried out on the same plots. Furthermore, added measurement of an isotopic tracer such as radiocarbon is of particular relevance in characterizing SOC dynamics. As a cosmogenic radionuclide, ^{14}C naturally exists in the atmosphere. However, nuclear weapons testing during the early 1960s nearly doubled its atmospheric concentration in the northern hemisphere, spreading then to the rest of the world (Trumbore, 2009). An agreement between the nuclear powers to stop atmospheric testing generated a peak concentration of ^{14}C in atmospheric CO_2 in the 1960s, with this excess or 'bomb' ^{14}C subsequently decreasing due to its incorporation into oceans and terrestrial ecosystems, as well as its dilution by fossil fuel-derived CO_2 from which all ^{14}C has been removed through radioactive decay (Trumbore, 2009). This bomb ^{14}C spike became a centrally relevant tracer for studying C dynamics (Levin et al., 2022). Combining radiocarbon and SOC measurements makes it possible to determine whether most of the stored soil C entered from the atmosphere in recent years or centuries. With this approach it is also possible to fit compartmental models of varying complexity to obtain an integrated assessment of the timescales of soil carbon cycling (Sierra et al., 2012, 2014).

In this work we document decadal changes in SOC and radiocarbon following the implementation of new management practices in a soil previously degraded by intensive agricultural cultivation. We focus specifically on the capacity of integrated crop-pasture systems to recover the C content of soils and to estimate how long this newly sequestered C can persist. To achieve this objective, we designed and adjusted dynamic compartmental models that represent the trajectory of soil C and radiocarbon of an experiment in which intensive agriculture was carried out for more than 20 years, whilst for the subsequent 35 years a conservation system of crops in rotation with perennial pastures was applied, which also included and intensification of management in the last decade.

In particular, we seek to answer the following questions:

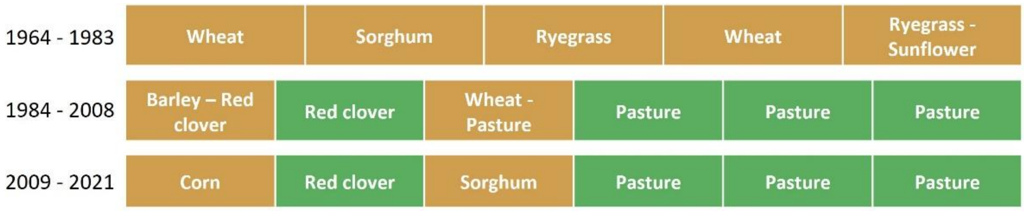
What are the SOC sequestration rates following the implementation of conservation management alternating crops with pastures?
What is the stability/persistence of the newly incorporated C?
Do new C inputs flow into highly stable/persistent compartments or are they vulnerable to future losses?

2. Materials and methods

2.1. Long-term experiment

The information used in this work is derived from an LTE installed by the National Institute of Agricultural Research (INIA) in 1963 at the La Estanzuela Experimental Station (Colonia, southwestern Uruguay; 34°20′33″ S, 57°43′25” W). The experimental site is located in the “Bioma Pampa” (Río de la Plata Grassland ecoregion), the largest grassland region in South America, with a temperate humid to sub-humid climate and characterized by intense land-use modification (Baeza et al., 2022).
The climate of the experimental site is humid temperate, with an average annual temperature of 16.9 °C. The highest temperatures occur in January (average maximum temperature of 29.04°C) and the lowest in July (average minimum temperature of 6.24°C), showing a marked seasonality. The mean annual precipitation is 1127 mm and the accumulated reference evapotranspiration is 1193 mm. The landscape consists of rolling hills and the soil is moderately acidic. The dominant soils of the experimental site are classified as fine, smectitic Vertic Argiudoll (Soil Survey Staff, 2014). They are characterized by a well-developed Bt horizon that typically occurs at ~30 cm depth, absence of rockiness, and medium to high fertility.
The LTE evaluates seven treatments that represent a gradient of agricultural intensity from continuous cropping to conservation systems of agriculture in rotation with perennial pastures. This work focuses on analyzing the temporal evolution of one treatment that has undergone management changes throughout its history, making it particularly suitable for addressing the questions posed in this study. Detailed information on the experimental site and the LTE can be obtained in González-Sosa et al. (2024).

The crop rotation system studied in this work, which we called 'Recovery system', presents three marked periods throughout the history of the experiment (Fig. 1). Initially, in the period 1964-1983, the system was essentially continuous cropping with occasional rotation with annual pasture production (ryegrass). Then, from 1984 onwards, the system changed to a conservationist objective with two-thirds of the rotation with pastures and one-third with cereal and oilseed crops. Specifically, the rotation is characterized by one year of red clover production between two years of crop production, followed by three years of a perennial pasture composed of white clover (*Trifolium repens* L.), bird's-foot trefoil (*Lotus corniculatus* L.), and tall fescue (*Festuca arundinacea* Schreb.). Concerning the rotation structure, the only change between 1984-2008 and 2009-2021 is the inclusion of summer C4 crops prior to the perennial pastures, instead of their planting in association with winter crops (barley/wheat) as was the case until 2008 (Fig. 1).



1964 - 1983	Wheat	Sorghum	Ryegrass	Wheat	Ryegrass - Sunflower	
1984 - 2008	Barley – Red clover	Red clover	Wheat - Pasture	Pasture	Pasture	Pasture
2009 - 2021	Corn	Red clover	Sorghum	Pasture	Pasture	Pasture

Figure 1. Crop rotation structure of the 'Recovery system' throughout the different periods of La Estanzuela LTE.

The three periods shown in Fig. 1 involved other management changes in addition to the crop sequence, essentially related to tillage. In the first period, all crops were established using conventional tillage (moldboard and disk plow). In the second period, a chisel plow was progressively implemented, and crops were established in association with pastures to reduce the frequency of soil tillage and time under fallow. Finally, from 2009 onwards, tillage activities were eliminated, and all crops and pastures were established in a no-till system. Additionally, to ensure a better growth of the pastures, sporadic hay harvests were carried out during this phase of the rotation since 2009.

2.2. Data used for model calibration

The plots have been sampled annually for SOC determination since the installation of the LTE. Sampling depth was down to 20 cm until 1996 and down to 15 cm thereafter. As discussed in previous work, no major changes in long-term trends are expected due to this modification of sampling depth since tillage interventions were carried out until 2008, which homogenized the surface soil layer (Grahmann et al., 2020). If there is an effect, it should be expressed only in the last years of the time series, after the definitive incorporation of the no-till system.

The samples obtained annually were processed at the Laboratory of Water, Plants and Soils of INIA La Estanzuela (Colonia, Uruguay) to determine C concentration by wet digestion until 2011 and by dry combustion from 2012 onwards. A bulk density value measured in 2021 (1.25 ± 0.044 Mg m^{-3}) was used for the SOC stock calculations.

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In parallel to obtaining the SOC time series, a sample archive of the experiment was created, storing a ground and dried subsample for all the samples obtained in the history of the experiment. Taking advantage of the availability of this unique source of information, we analyzed samples corresponding to 21 time-distributed points for $\Delta^{14}C$ at the radiocarbon analysis laboratory of the Max Planck Institute for Biogeochemistry (MPI-BGC; Jena-Germany). The details on sampling and laboratory procedures for obtaining the SOC and $\Delta^{14}C$ time series are the same as those described by González-Sosa et al. (2024) concerning other agricultural treatments of the same LTE.

2.3. Preliminary analysis of SOC trends

As an exploratory analysis of the changes experienced by the Recovery system over time, linear regression models were adjusted to describe the SOC stock variations for each of the three periods shown in Fig. 1. In turn, the continuous cropping system of the LTE was included in this analysis (data extracted from González-Sosa et al. (2024)) to compare the Recovery System with a treatment that continued an intensive agriculture management until the present day. This treatment maintained a cropping sequence similar to that of period 1 of the Recovery system until the present.

2.4. SOC modeling

To generate information about the soil internal dynamics of the Recovery system responsible for the measured SOC and radiocarbon trajectory, we designed and parameterized compartmental models in the form of systems of ordinary differential equations (ODE's). These ODE's systems can be generalized to represent any level of complexity (number of compartments and transfer schemes between them) as follows (Sierra et al., 2012, 2014) (Eq. 1):

$$\frac{dC(t)}{dt} = I + AC(t),$$

where *C(t)* is an n-dimensional vector, representing the stock of C at each time t in each of the n compartments into which the SOC is partitioned; *A* is an *n* x *n* square matrix containing the output rate constants of each compartment on its main diagonal and the transfer coefficients between compartments in the off-diagonal entries, *I* is a vector containing the C inputs from outside the system to each of the *n* compartments.

The formulation of Eq. 1 can be used to generate a parallel model representing the specific radiocarbon dynamics, taking into account the proportion of radiocarbon in the atmospheric carbon input (which varies by year) and in the different compartments of the system at any given time, plus an additional output process which is the radioactive decay of this radioisotope (^{14}C has a radioactive decay constant of 1/8267 yr^{-1}). Modeling the radiocarbon dynamics in addition to the dynamics of the total C flowing through a compartmental system allows us to use information about this isotope as a constraint to the model parameterization that greatly improves our ability to represent reality. Moreover, the consolidation of all the available information in a mathematical structure as in Eq. 1 enabled us to generate information about the complexity of the analyzed system (i.e. number of necessary compartments and transfers between them to correctly represent the SOC dynamics) as well as the cycling rates of each pool.

2.4.1. Model complexity and mathematical optimization

To correctly represent the measured SOC and radiocarbon data and evaluate the persistence of the newly incorporated C, we tested two alternative model structures with different degrees of complexity. We initially fit a two-pool compartmental model structure with transfers in series (Fig. 2a). In this structure, C enters the system through a fast pool and is then transferred to a slow pool in a process that depends on the output constant rate of the fast pool (k_1) and the parameter α that determines how much of the mass leaving the fast pool is transferred to the slow pool. To assess whether consideration of a more complex structure was necessary, we fit a three-compartment model in series with a compartment of intermediate kinetics between the two pools of the previous model (Fig. 2b). This version allows us to evaluate whether the system's dynamics is adequately represented by C transfers among a compartment that cycles on annual timescales, another that cycles over years to decades, and a more persistent compartment that cycles over centuries to millennia.

Regarding the initial conditions of the two-pool model, the average SOC content at the beginning of the experiment (year 1964) was taken as the initial value of SOC stock. Based on an initial manual model fitting process, we set the $\Delta^{14}C$ value of the slow pool at -70 ‰, in order to adequately describe the soil radiocarbon trend measured in the initial years of the LTE and taking into consideration that a slow-kinetic pool comprises the majority of organic C in these soils (González-Sosa et al., 2024). Regarding the fast pool, its initial $\Delta^{14}C$ value was defined at zero, considering that the signature of this compartment couples almost immediately to the atmospheric signature regardless of the starting value (González-Sosa et al., 2024), so starting at an approximate value of the atmosphere before the nuclear tests was considered a reasonable assumption. In addition, another parameter was adjusted to define the initial SOC partitioning between the fast and slow pool at the start of the experiment (t_0 = 1964) (see Figure 2).

Concerning the three-compartment model, the same initial bulk SOC content was set as in the simple model. For radiocarbon, the initial signatures of the fast and slow pools were defined in the same way as in the previous case, and the initial signature of the intermediate pool was set as the average of the two previous ones. As in the simpler two-box model, a parameter defining the initial proportion of C in the slow pool (at t_0 = 1964) was optimized, while the remaining mass was equally distributed between the fast and intermediate pools.

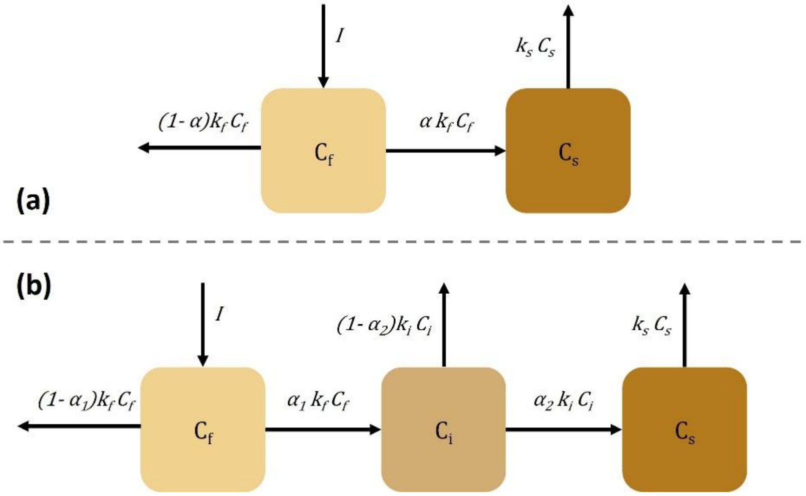

Figure 2. Compartmental model structures used to represent SOC stock and radiocarbon information. (a) Two-compartment model in series and (b) Three-compartment model in series. C_f: fast pool C stock; C_i: intermediate pool C stock; C_s: slow pool C stock; k_f: fast pool outflow rate constant; k_i: intermediate pool outflow rate constant; k_s: slow pool outflow rate constant; α: C transfer coefficient from the fast pool to the slow pool (2-box model); α_1: C transfer coefficient from the fast pool to the intermediate pool (3-box model); α_2: C transfer coefficient from the intermediate pool to the slow pool (3-box model).

The models were defined in three periods, considering the management modifications in each of the LTE phases (Fig. 1). The parameter sets were defined for each of the three periods and for each model structure, and the value of the state variables at the start of the periods two and three were set equal to their final values at the end of periods one and two, respectively.

Soil C inputs, necessary to model SOC dynamics, were considered constant, but with values that differed for the first versus second and third periods of the experiment. In the initial phase (1964-1983), we assumed the annual input rate reported by González-Sosa et al. (2024) for a continuous cropping system in the same LTE (2.87 Mg C ha^{-1} yr^{-1}). Then, an average annual value of C inputs was calculated for periods 2 and 3 (i.e. 1984-2021) (6.68 Mg C ha^{-1} yr^{-1}), when an integrated crop-pasture system was established, based on the procedure described in González-Sosa et al. (2024) using the plant productivity monitoring database of the LTE plots. To assess possible reductions in C inputs after 2008 due to the implementation of no-till that can affect SOC and radiocarbon dynamics, we performed a sensitivity analysis by extending the period-2 parameterization to the end of the experiment (periods 2 + 3) and imposing two reduced-input scenarios during period 3 (20% and 40% reductions in C inputs).

The models' parameterization was conducted using the FME library (Soetaert and Petzoldt, 2010) in R version 4.4.0. We generated a cost function that calculates the sum of the squared residuals between the model estimates and the data, which was minimized in the model fitting procedure. Initially, the Levenberg-Marquardt algorithm was applied to find an initial optimal set of parameters that was used as a starting point in a Markov Chain Monte Carlo (MCMC) procedure to estimate the probability distribution of the unknown parameters. Finally, the uncertainty of the fitted models was propagated to the outputs in an iterative procedure of parameter set drawing and model execution, whereby the most likely parameter values were more frequently represented in the outputs. RMSE was calculated as fit statistics of the models to the data.

2.4.2. Processing of new C inputs

To evaluate the stability/persistence of the new C inputs, we used the model with the structure that best represented the measured data to describe the fate of the C inputs since the LTE installation. The mass of new C inputs retained by the system per unit of time depends on the input rate, the decay constant of each pool, and the internal transfer scheme between pools (with the latter two defining the A matrix) (Eq. 1; Fig. 2). Since the contribution of new inputs to C stocks does not depend on initial C conditions (given that we are working with a linear model), we defined the C stock of all pools at $t = 0$ (1964) as zero. Subsequently, we took the parameter distributions that emerged from the optimization described in section 2.4.1 and ran the model since 1964. Through this procedure, we were able to evaluate how new C inputs (those occurring after the LTE installation in 1964) were allocated to the compartments of different kinetics represented in the model. This exercise was performed with the same procedure of propagation to the model outputs of the uncertainty contained in the parameter populations, as described in the previous section.

3. Results

The three periods of the studied Recovery system clearly displayed different SOC dynamics (Fig. 3). The first stage, which lasted from the installation of the experiment in 1964 to 1984, was characterized by a low intensive agricultural system (one crop per year) and systematic application of tillage, and generated a SOC decrease at a rate of 0.26 Mg ha^{-1} yr^{-1} (Fig. 3). This period behaves the same as the system still maintained in continuous cropping (CC) and whose dynamics we have already characterized in a previous study (González-Sosa et al., 2024). The installation of an integrated crop-pasture rotational system in 1984 generated a process of SOC increase at a rate of 0.65 Mg ha^{-1} yr^{-1} (Fig. 3). This period of SOC stock increase stopped in 2008, when a series of management changes listed in section 2.1. occurred, which determined the SOC stock to decrease at a rate of 1.11 Mg ha^{-1} yr^{-1} (Fig. 3).

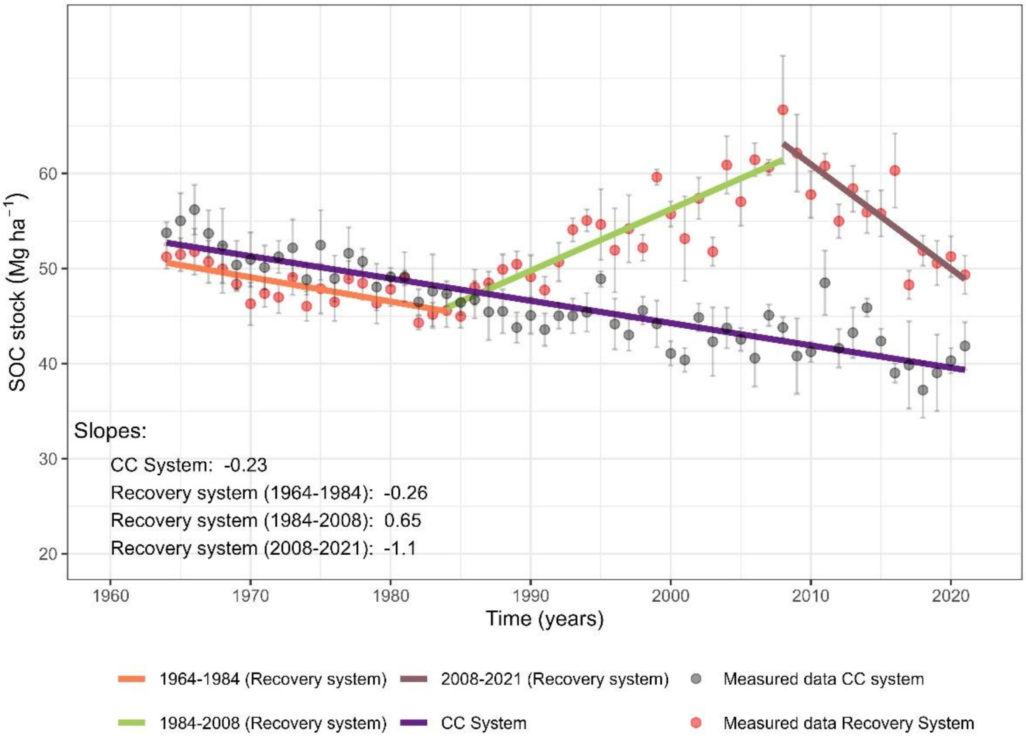

Figure 3. SOC time series of the Recovery system throughout the different periods of the LTE. CC system (González-Sosa et al., 2024) is shown as a reference of a system that is still in continuous agriculture until today.

Fitting models of varying complexity to the LTE data showed the need for including an intermediate kinetics compartment in a three-pool structure to adequately represent the joint evolution of SOC and radiocarbon (Fig. 4). The simpler mathematical structure of two compartments in series (Fig. 2a) was able to represent very adequately the SOC dynamics (Fig. 4a), correctly capturing the three stages related to management changes and the associated trend shifts in SOC stock evolution. However, this model did not correctly represent radiocarbon dynamics, not being able to capture the decreasing trend of this variable after 2008 (Fig. 4b). The more complex three-compartment model in series (Fig. 2b) captured the SOC temporal dynamics in a similar way to the previous model, although there was an important decrease in the uncertainty of the estimation, with a lower standard deviation and 95% confidence interval (Fig. 4c) compared to the two-compartment model (Fig. 4a). However, this similar representation of the SOC temporal evolution responded to completely different internal dynamics between the two mathematical representations. This was evidenced by the completely different trajectory of the temporal evolution of the $\Delta^{14}C$ signature between the two structures (Fig. 4b; Fig. 4d). The three-compartment model correctly captured the measured temporal changes, being able to represent the $\Delta^{14}C$ decrease that occurred after 2008 (Fig. 4d) in contrast to what happened with the simpler model structure (Fig. 4b).

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The root mean square error (RMSE) between the median value of the model uncertainty propagation and the measured SOC data was practically equal for both model complexities (2.23 Mg ha^{-1} for the 2-box model and 2.31 Mg ha^{-1} for the 3-box model), because the simplest model already adequately represented the dynamics of this variable. However, the better behavior of the most complex model was visualized in the important decrease of the $\Delta^{14}C$ RMSE, which varied from 15.22 ‰ in the 2-box model to 9.25 ‰ in the 3-box model.

The contrasting internal dynamics of the two models implies a different distribution of C between compartments of different stability (Fig. 4a,c). The two-pool model explained the increase in the SOC stock that occurred after 1984 and its subsequent decrease from 2008 onwards as a variation of the slow pool (Fig. 4a). However, the variation of this pool could not correctly represent the decrease of $\Delta^{14}C$ on a short time scale, as occurred after 2008 (Fig. 4b). Allocating the increase in C stocks during period 2 to this slow-cycling pool, whose radiocarbon signature is strongly buffered toward negative values due to the large amount of legacy C it contains, prevents it from reaching high $\Delta^{14}C$ values. Consequently, its subsequent loss cannot mathematically generate a negative leverage on the bulk radiocarbon signature sufficient to explain the marked decline in $\Delta^{14}C$ measured from 2008 onward. This inability of the model to correctly capture the radiocarbon trend (Fig. 4b) demonstrates that a two-compartment structure was not sufficient to correctly represent the system, as the fast compartment is too reactive to reflect the management changes and the slow compartment falls short of reacting to them.

The better ability of the three-box model to represent the data (Fig. 4c,d) occurred because most of the SOC stock variations were explained by C stock changes in a pool with intermediate kinetics between the compartments represented in the simpler model. As was the case in the two-box model, the drop in SOC stock in the period of continuous agriculture (1964-1984) was explained by a decrease in the slow pool (Fig. 4c). However, the subsequent recovery in the 1984-2008 period was not explained by this compartment, which remained highly stable in its C content despite the recovery of the total stock. In fact, this recovery was due to a significant increase in the stock of the intermediate pool. Having stored material with a recent $\Delta^{14}C$ isotopic signature (with very high values due to enrichment from the bomb spike), the subsequent abrupt decline in this pool's stock from 2008 onwards successfully explained the decrease in the soil radiocarbon signature (Fig. 4d).

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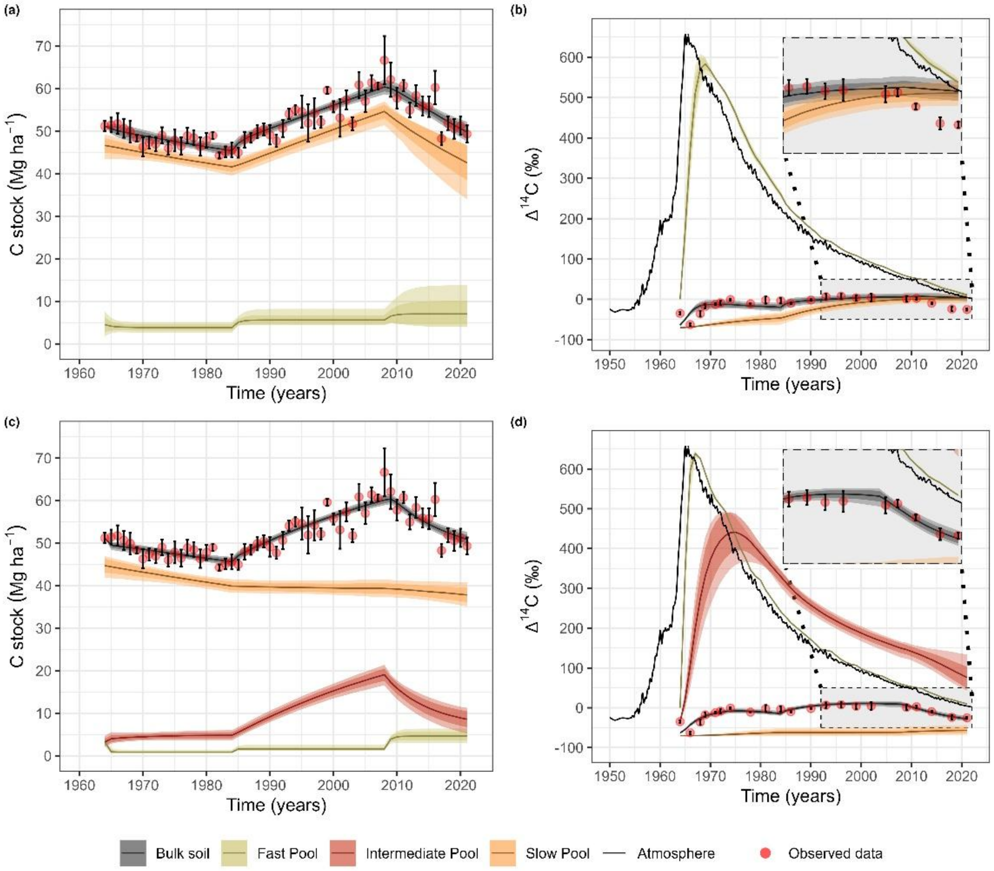

Figure 4. Predictions for the Recovery System obtained with the two-box model (a, b) (Fig. 2a) and the three-box model (c, d) (Fig. 2b) of the temporal evolution of SOC stock (0-20 cm) (a, c) and of the natural abundance of radiocarbon derived from the ^{14}C atmospheric peak (b, d). Time trends are shown for bulk soil and each of the kinetic compartments considered by each model structure. The propagation of model uncertainty to the estimated variables was obtained by sampling the posterior distribution of parameters (standard deviation is represented as a dark ribbon and the 95% confidence interval as a light ribbon).

The three-box model, which proved to be more adequate to describe the measured data, consists of a fast, an intermediate and a slow pool with clearly distinct turnover rates (Table 1). The fast pool cycled 1–2 orders of magnitude faster than the intermediate pool, which in turn cycled 1–2 orders of magnitude faster than the slow pool. In addition to the rise in the C input rate to the system, the increase in C stock in the intermediate compartment that occurred in the period 1984-2008 was mainly explained by a 84.4% decrease in the output rate constant of this pool. This factor explained the large increase in C stock of this pool and the whole system despite the decrease in the proportion of C flowing into the intermediate pool per unit mass flowing out of the fast pool (α_1) during period 2 (Table 1). With respect to the slow compartment, its output rate constant decreased 84.1% in period 2 relative to period 1. This reduction halted the net loss previously observed in this compartment, which consequently maintained a high degree of stability in its C stock during this period. However, the increase in total system C stocks during period 2 was not reflected in an increase in the C content of the slow pool, due to a strong decrease in the cycling rate of the intermediate pool, which resulted in a reduced flux to the slow pool (Table 1). Finally, in the last period there was a significant increase in the outflow rate constant of this pool (k_3) that was not compensated by the increase in the flow of C to this pool due to the rise in the cycling rate of the intermediate pool (k_2), which resulted in higher net C losses from the slow pool (Table 1). Throughout the history of the experiment, the slow pool was consistently in negative balance, except during the recovery phase (period 2), when it reached a zero balance and maintained stock stability. The increase in system C stocks during period 2 occurred exclusively through the allocation of new C to an intermediate-cycling pool. After 2008, the observed decline resulted from the destabilization of this intermediate pool as well as a substantial loss from the slow pool. These losses were partially offset by an increase in the fast compartment (Fig. 4c; Table 1).

Table 1. Results of parameter optimization through MCMC for the three-compartment model in each period of the experiment.

	k_1			k_2			k_3		
	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
Mean	**3.35**	**4.00**	**1.50**	**0.18**	**0.028**	**0.13**	**6.9E-03**	**1.1E-03**	**5.7E-03**
SD	**0.87**	**0.71**	**0.36**	**0.06**	**0.016**	**0.04**	**1.9E-03**	**8.8E-04**	**2.6E-03**
Min	1.02	1.64	1.00	0.01	0.010	0.04	1.7E-04	1.0E-06	3.4E-06
Max	5.00	5.00	2.59	0.38	0.103	0.32	1.0E-02	5.0E-03	1.0E-02
Q1	2.72	3.53	1.19	0.14	0.016	0.11	5.7E-03	4.0E-04	3.6E-03
Q2	3.31	4.12	1.44	0.17	0.024	0.13	7.1E-03	8.9E-04	6.0E-03
Q3	4.01	4.59	1.75	0.21	0.035	0.16	8.5E-03	1.6E-03	8.0E-03
1/k [1]	0.30	0.24	0.69	5.80	41.49	7.72	140.27	1127.29	166.41

	α1			α2			Initial Cs
	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3	proportion[2]
Mean	**0.29**	**0.14**	**0.12**	**0.067**	**0.056**	**0.061**	**0.87**
SD	**0.06**	**0.03**	**0.07**	**0.031**	**0.042**	**0.038**	**0.03**
Min	0.07	0.09	0.00	0.000	0.000	0.000	0.75
Max	0.40	0.27	0.39	0.150	0.150	0.150	0.96
Q1	0.25	0.12	0.07	0.046	0.021	0.031	0.85
Q2	0.29	0.14	0.12	0.068	0.046	0.052	0.87
Q3	0.33	0.16	0.17	0.086	0.084	0.090	0.89

Note: SD: standard deviation; Q1: first quartile; Q2: median; Q3: third quartile.

[1] 1/ki is the intrinsic first-order decomposition timescale of each pool. In a multi-pool model with inter-pool transfers, 1/ki should be interpreted as the characteristic timescale of loss from pool i (i.e., its own turnover time), not as the residence time, age, or transit time of carbon in the system as a whole. The median value of each ki was used for the calculation.

[2] Initial Cs proportion is the proportion of the total C stock contained in Cs (slow pool) at the beginning of the simulation (year 1964).

Through the theoretical exercise of applying the structure and parameterization of the three-compartment model to a system initialized with SOC stock = 0 in 1964, we characterized how the model processes the C inputs that occurred over the history

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of the LTE and how these inputs were allocated to compartments of different kinetics (Fig. 5), independently of the dynamics of legacy C (i.e. the soil C stock present prior to the experiment installation). At the time when the maximum SOC stock occurred (year 2008), the SOC coming from new inputs (those occurring during the history of the experiment - after 1964 -) was partitioned among the fast pool (7.4%), the intermediate pool (87.3%), and the slow pool (only 5.3%) (Fig. 5). This means that, of the total stock of the slow compartment in that year (39.9 Mg ha^{-1}, Fig. 4c), approximately 2.9% originated from new inputs after 1964, while the remainder was older.

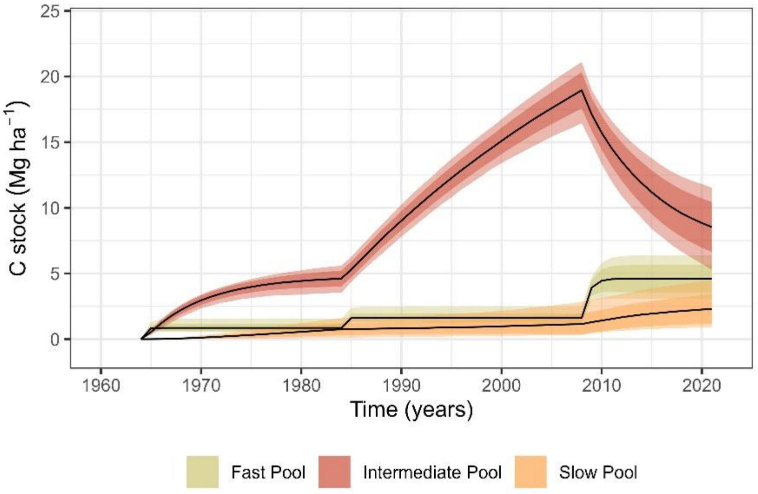

Figure 5. New C incorporated during the LTE period (after 1964) by pool during the LTE period (after 1964) in the three-compartment model. The propagation of model uncertainty to the estimated variables was obtained by sampling the posterior distribution of parameters (standard deviation is represented as a dark ribbon and the 95% confidence interval as a light ribbon).

To test the sensitivity of the results to the assumption of constant C inputs between periods 2 and 3, we conducted an analysis in which the parameterization of period 2 was held constant, while imposing reductions of 20% and 40% in C inputs during period 3. This analysis allowed us to assess whether such potential reductions on their own could explain the observed changes in the system dynamics, given that the management changes implemented in 2008 (complete elimination of tillage operations, modifications in crop sequence within the rotation, and occasional hay removal to ensure proper establishment of pastures and crops) may have led to an overestimation of C inputs during period 3. Considering only a 20% reduction in C inputs during period 3, the system would continue to accumulate C (Fig. 6a), whereas under an extreme scenario of a 40% reduction in C inputs, the system would cease accumulating C and reach a state of stability, and be unable to represent the significant measured reduction in total C stock (Fig. 6c). In contrast, the system proved insensitive to these changes with respect to its Δ^{14}C dynamics during period 3 (Fig 6b,d), indicating that destabilization and rapid losses of bomb-^{14}C-enriched C from the intermediate pool are required to explain the observed decline in the bulk ^{14}C signature during this period.

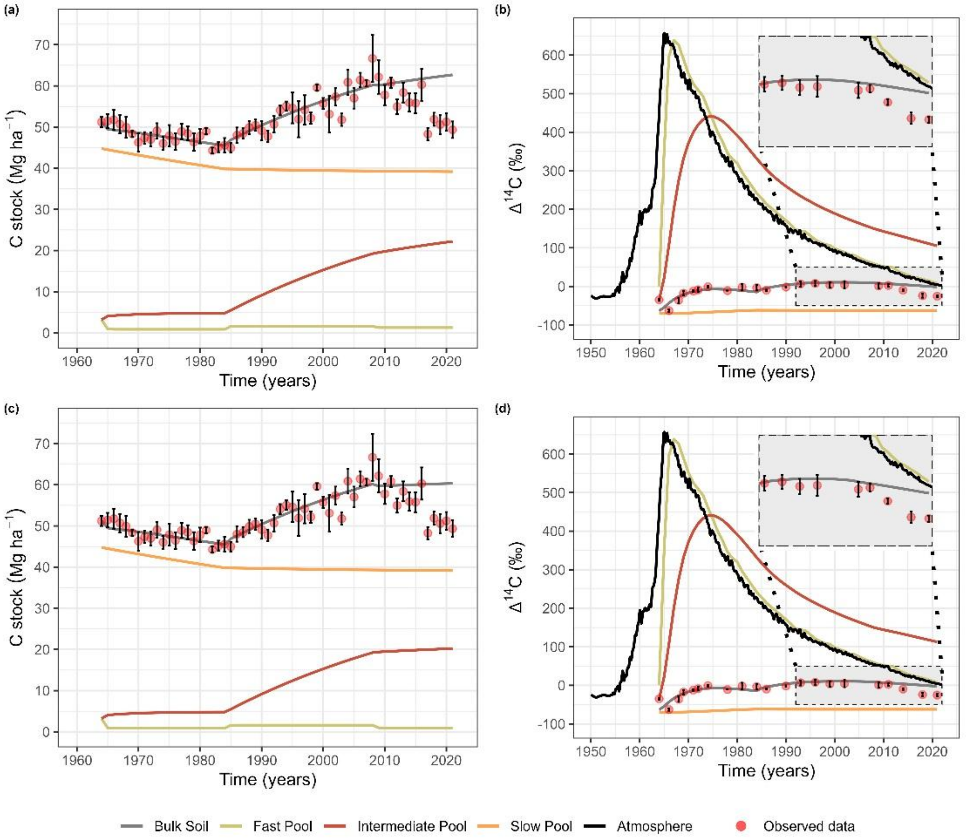

Figure 6. Predictions for the Recovery System obtained using the three-box model of the temporal evolution of SOC stocks (0–20 cm) (a, c) and of the natural abundance of radiocarbon derived from the nuclear bomb peak (b, d), assuming that the parameterization of period 2 remains unchanged during period 3 and that C inputs during period 3 are reduced by 20% (a, b) and 40% (c, d). Model simulations were performed using the median value of each parameter distribution.

4. DISCUSSION

Maintaining or increasing the SOC stock, and particularly in compartments of high stability, is a relevant goal for climate change mitigation (Paustian et al., 2016; Prairie et al., 2023). The evaluation of a conservation management system based on crop-pasture rotations after 20 years of continuous agriculture on a 60-year LTE showed that it is possible to recover the SOC stock at remarkably high rates on previously degraded soils (Fig. 3).

This management system represented in the 'La Estanzuela' LTE is characterized by an initial phase of SOC loss at a rate of -0.26 Mg ha^{-1} yr^{-1} in the period 1964-1984, when it had a continuous cropping sequence. The SOC loss rate in this phase had the same magnitude as previously described for continuous cropping systems, and is explained by destabilization and loss of legacy C in slow-cycling compartments (González-Sosa et al., 2024). The decrease in tillage frequency, as well as the increase in C inputs associated with the incorporation of perennial pastures allowed the soil to gain on average 0.65 Mg ha^{-1} yr^{-1} of SOC in the period 1984-2008. The increase in SOC in this period is similar in magnitude to results reported in other works that have studied the SOC recovery capacity of formerly tilled agricultural sites that were reconverted to grasslands, for which Kämpf et al. (2016) report a SOC increase rate of 0.72 Mg ha^{-1} yr^{-1}. Kurganova et al. (2014) report similar recovery rates (0.96 Mg ha^{-1} yr^{-1}) on abandoned agricultural land in Russia. Although these previous works, and others in which the implementation of ecological restoration strategies has been evaluated, suggest that it is possible to recover previously lost SOC, evidence has been found that it is unlikely to achieve a level of recovery that fully compensates for previous losses (Ascenzi et al., 2025; Pan et al., 2025).

Our results imply that it is possible to "repay" the SOC deficit due to historical losses caused by agricultural activities (Sanderman et al., 2017), due to the high capacity shown by this management system to recover SOC content in the period 1984-2008. However, the C gained during this phase proved to be highly vulnerable to subsequent losses. The abrupt change in the SOC trajectory in 2008 and the availability of high temporal resolution radiocarbon data allowed us to determine how the C accumulated during the recovery phase (1984-2008) was allocated among compartments with contrasting kinetics and persistence. The allocation of this new C into kinetically stable compartments (i.e. slow pools that cycle over centuries to millennia) does not appear to be straightforward, as the vast majority of C inputs during the recovery phase (1984–2008) flowed into an intermediate-kinetic compartment (Fig. 5) that was largely lost after 2008 (Fig. 4c, Fig. 5).

The fitting of models of different structural complexity (two-compartment model and three-compartment model in series) showed that a very low proportion of the C inputs that occurred during the period of SOC increase (1984-2008) flowed into the slow pool associated with higher persistence (Fig. 4c,d; Fig. 5). Then, environmental or management changes that occurred subsequently led to an important and selective loss of that previously gained SOC (Fig. 4c; Fig. 5), as well as to a destabilization of the slow compartment itself, which experienced a decline in its C stock despite receiving increased input fluxes due to the enhanced decomposition of the intermediate pool. The increase in SOC experienced by the Recovery System in the period 1984-2008 was allocated to a compartment of intermediate kinetics (Fig. 4c; Fig. 5) and low stability (cycling on the order of years to decades), whose subsequent loss mainly explained the SOC decline that was measured after 2008 (Fig. 4c), being the three-box scheme the most appropriate to represent the system. The conceptualization of SOC dynamics including this compartment that cycles on the order of years to decades was necessary to explain the clear decline in the radiocarbon signature that occurred (in addition the SOC decline) after 2008, which can only be explained with the loss of strongly bomb-^{14}C-enriched material incorporated into the soil over previous decades and whose removal strongly reduced the soil $\Delta^{14}C$ signature. These results are accord with Kuzyakov (2011), who found that the separation of the total SOC into two compartments is insufficient to adequately describe the processes responsible for its dynamics. In contrast to the more complex model, the two-compartment model failed to reproduce the full SOC and radiocarbon dataset, as the fast pool cycles too fast to preserve bomb C, while the slow pool strongly dilutes the new inputs into a ^{14}C depleted pool. This simpler model represented the 1984-2008 SOC increase as an increase in the slow compartment (Fig. 4a), implying that this soil pool containing the majority of soil C can respond rapidly to input changes (Fig. 4b), contrary to what we have previously described for other treatments of the same LTE (González-Sosa et al., 2024), and demonstrating the 2-pool model (analogous to the conceptualization of particulate and mineral-associated carbon) as a mathematical scheme incapable of representing the post-2008 radiocarbon decline measured at the site.

While this study provides valuable insights, one limitation is that we lack sufficient information to provide a clear mechanistic explanation for the decline in SOC stocks after 2008, as several management factors changed simultaneously at the experimental site. This decrease may be associated with management changes introduced that year, which could have effectively reduced C inputs to the mineral soil due to modifications in the crop sequence, occasional removal of aboveground biomass, and a possible increase in SOC stratification resulting from the complete elimination of tillage and the lack of initial adaptation of the system to the full implementation of no-tillage practices (Cai et al., 2022). Regarding the potential effects of fully implementing no-till farming without any sporadic tillage, it has been suggested that the incorporation of aboveground carbon inputs into the mineral soil may be slower (Cai et al., 2022; Six et al., 2004). This would result in a significant stratification of carbon inputs if biological activity does not promote its incorporation at a significant rate, thereby reducing the contact between this material and the soil mineral phase. This would lead to increases in surface particulate organic matter, which is coherent with the rise in the fast pool stock that we identified in our model after 2008, despite the decline in total stock. Another relevant factor in explaining the changes observed after 2008 may be the shift in the crop sequence (Fig. 1), which involved an intensification process in which pastures were no longer established in association with the preceding crop, thereby shortening the time under perennials (including legumes), and increasing the length and frequency of fallow periods. This may have reduced average C and N inputs to the soil, but its main effect was to alter their temporal distribution, creating longer intervals without C additions that could favor SOC oxidation.

In any case, even if a potential reduction in C inputs is assumed, due to an equifinality problem the optimization of the model parameters would lead to proportional adjustments of the output rate constant of the first compartment (k_1) and the transfer coefficient to the subsequent compartment (α_1), while leaving the remaining parameterization unchanged. This limits our ability to infer a unique mechanistic explanation for the causes of SOC destabilization after 2008 based on the available information. Nevertheless, a sensitivity analysis in which the parameterization of period 2 was held constant during period 3, while simultaneously reducing C inputs after 2008 by 20% and 40% in this last period, showed that such potential reductions alone cannot explain the observed decline in SOC stocks and have virtually no effect on explaining the decrease in $\Delta^{14}C$ (Fig. 6). Correctly reproducing the observed $\Delta^{14}C$ dynamics requires the predominant destabilization and loss of bomb-^{14}C-

enriched C from the intermediate pool, reinforcing the robustness of the finding that highlights the high vulnerability of C gains during the recovery period (1984-2008).

Moreover, the absence of a net increase in the slow pool during the SOC recovery period (1984-2008) may indicate that SOC stabilization processes occur at very low rates and take long periods of time as discussed in previous studies (He et al., 2016). However, maintaining high C input rates may be necessary to avoid losses of that old C (Daly et al., 2021; González-Sosa et al., 2024) because an apparent stabilization of the SOC stock of this compartment occurred in the period 1984-2008 (Fig. 4c). This interpretation is consistent with the SOC behavior after 2008, when a period of decline in SOC stock started mainly due to the predominant loss of the intermediate compartment, but also due to the destabilization of the slow compartment itself (Fig. 4c). Previous work indicate that in the absence of an adequate nutrition of the microbial biomass by plant inputs to the system, there may be destabilization of C that already had a higher degree of microbial transformation to provide those nutritional requirements (Hicks et al., 2021) through previously stabilized C mining processes (Daly et al., 2021).

The ability of conservation management systems to recover stable C is not consistent across studies. Some evidence indicates that although actions aimed at the recovery of degraded sites achieve an increase in total C contents on timescales of decades, they are only able to increase the stock of labile C (i.e. C that cycles in the order of years) but not in compartments associated with greater persistence (He et al., 2024; Xu et al., 2020). This implies a risk because the gained C would be susceptible to oxidation if climatic or management conditions change (Xu et al., 2020). Rui et al. (2022), in a 29-year LTE in North Central United States, found that the implementation of conservation practices (no-tillage, crop rotations, legume incorporation and manure addition) in agricultural systems failed to increase the mineral associated organic C (MAOC) stock, limiting their role as long-term C sinks. However, these authors did find that properly managed permanent pastures were able to increase the C stock associated with the mineral phase (Rui et al., 2022). Other also found that well-managed pastures can increase both the total SOC stock and its degree of stabilization (Mosier et al., 2021). Gao et al. (2025) report an increase in particulate organic C (POC) and MAOC in the 0-10 cm layer but a decrease in the 10-20 cm layer after no-tillage system implementation. However, Prairie et al. (2023), in a meta-analysis, found that practices included in the so-called "regenerative agriculture" (no-tillage, intensification of agricultural systems and integrated crop-livestock systems) were able to increase total SOC content, as well as MAOC and POC. It is important to highlight that comparisons between previous studies and this work are limited by the fact that laboratory fractionations do not necessarily correspond directly or completely to the kinetic compartments inferred through modeling (as was done in this work). Nevertheless, these laboratory approaches can provide a useful proxy for approximating the functional roles and stability levels of different SOC components (Lavallee et al., 2020).

Manzoni and Cotrufo (2024) indicate that soils that have lost C, in which stabilization is less limited by the saturation of mineral surfaces, would have a greater capacity for C and N stabilization (flow towards compartments associated with the mineral phase), and that these processes would, in turn, be intensified in soils with high clay content. However, the results found in this work do not align with those findings. We found that after a period of intensive agriculture the installation of a highly productive conservation system achieved very high rates of SOC increase but did not allocate that C into persistent compartments (Fig. 4c; Fig. 5). To successfully promote long-term SOC sequestration, we should emphasize strategies that stabilize atmospheric C in slow-cycling compartments (Poeplau et al., 2018; Prairie et al., 2023; Rui et al., 2022; Tangarife-Escobar et al., 2024). However, as found in other studies, our results demonstrated that the vast majority of C inputs flow rapidly through the system and very little is stored in compartments of high stability (Sierra et al., 2023; Stoner et al., 2021; Tangarife-Escobar et al., 2024). Our results are consistent with most of the C inputs that accounted for the total SOC increase in the period 1984-2008 being allocated into a compartment of intermediate kinetics (Fig. 4c; Fig. 5) that is highly susceptible to future environmental or management changes.

Previous work has suggested that soil C persistence may arise from the functional complexity of soil microbial communities, emerging from interactions between the spatial and temporal variability of microbial communities and the diversity of decomposable substrates. This view implies that management aimed at C sequestration requires sustained attention, because stability emerges from delicate and complex ecosystem processes (Lehmann et al., 2020). Although we were unable to provide a unique mechanistic explanation for the SOC decline after 2008, the results are nevertheless informative in highlighting the highly transient nature of SOC dynamics. The dataset is consistently explained by an accumulation of the new C in an intermediate-cycling compartment and very limited transfer to a slow, persistent compartment, and a notable shift in the cycling rates of both pools at a 2008 inflection point (Fig. 4; Table 1). This shift led to the substantial loss of the C gained during the preceding recovery phase from the intermediate compartment and to destabilization of the slow compartment, which within the framework of our model can be interpreted as new losses of legacy C. Overall, this long-term time series indicates that the retention of C in soil and its effective maintenance as "sequestered" C is fragile and strongly dependent on the persistence of environmental and management conditions. In our case, the capacity to allocate the C gains of the recovery phase into a slow, highly persistent compartment was essentially negligible, and relatively modest management changes were sufficient to destabilize the system and reverse previously achieved gains.

This accumulated evidence and the dynamics observed in this experiment lead us to suggest that land management policies should seek to achieve two fundamental objectives. On the one hand, to avoid the expansion of the agricultural frontier, since the reestablishment of persistent C compartments lost with tillage can take long periods of time. On the other hand, to promote the establishment of agricultural systems that minimize tillage interventions and maximize C inputs to minimize the loss of previously stabilized C. Based on accumulating evidence from this and other studies, initiatives such as the 4 per mille (Minasny et al., 2017) should be seen only as complementary activities to a reduction of emissions from fossil fuel combustion and land use change, rather than as a mechanism that can exert an important effect on climate change mitigation per se. Likewise, it seems to be more realistic to highlight the importance of improving SOC stock levels because of the enormous number of soil properties that depend on organic matter content (Reeves, 1997; Rubio et al., 2021), rather than focusing on our actual capacity to achieve significant net SOC sequestration in stable long-term compartments at human scales to offset climate change.

5. CONCLUSIONS

The analysis of a SOC time series from a 60-year LTE, combined with high temporal resolution radiocarbon data, allowed us to generate novel insights into the SOC recovery potential of agricultural sites and the long-term persistence of the sequestered carbon. The trajectory of SOC and soil ^{14}C was mathematically represented by compartmental dynamic models and the use of a three-pool structure in series with pools of contrasting kinetics was necessary to correctly represent the dynamics of the system.

Our results indicate that it is possible to rapidly recover the SOC stock lost during prolonged agricultural land use by incorporating perennial pastures in agricultural rotations. In turn, this recovery process can occur over relatively short periods of time (years to decades). However, there was minimal allocation of the newly accumulated SOC to compartments that cycle at low rates and behave as kinetically persistent. This finding emerged from the need to explain observed declines in SOC stock and Δ^{14}C signature by allocation of most of the C accumulated during the SOC recovery phase to a third compartment having intermediate kinetics and strong enrichment in bomb-derived ^{14}C that could be rapidly lost, with minimal transfer of C into more persistent (century-millennial cycling) C pools.

This evidence indicates the importance of joining efforts in the conservation of old C existing in soils that are unaffected or only minimally affected by human activity. Although it is essential to increase SOC stock in previously managed systems and in soils with different degrees of degradation, both for the beneficial effect in global climate and for improving soil health, it remains debatable whether the transfer of such gains into stable, long-lasting carbon reservoirs occurs on timescales relevant for climate change mitigation. Our results also show that sustaining carbon gains requires long-term implementation of these efforts to prevent rapid losses. Accordingly, incentive policies should support practices that both preserve legacy soil carbon and maintain recovered carbon stocks.

Code, data, or code and data availability

Code and data are available for review at the following git repository: https://github.com/maxigon-23/data_and_code_gonzalez_et_al_26. It will be published with a DOI that can be cited in the publication.

Author contributions

Conceptualization: MGS, CAS, MVP. Data Curation: JAQ, MVP. Formal analysis: MGS. Funding acquisition: MVP. Investigation: MGS, MVP, CAS, JAQ, WEB, ST, ATE. Supervision: MVP, CAS. Writing – original draft preparation:

MGS. Writing – review and editing: MGS, MVP, CAS, JAQ, WEB, ST, ATE. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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