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Defining Quantitative Targets for Topsoil Organic Carbon Stock Increase in European Croplands: Case Studies With Exogenous Organic Matter Inputs

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The EU Mission Board for Soil Health and Food proposed a series of quantitative targets for European soils to become healthier. Among them, current soil organic carbon (SOC) concentration losses in croplands (0.5% yr^{-1} on average at 20 cm depth) should be reversed to an increase of 0.1–0.4% yr^{-1} by 2030. Quantitative targets are used by policy makers to incentivize the implementation of agricultural practices that increase SOC stocks. However, there are different approaches to calculate them. In this paper, we analyzed the effect of exogenous organic matter (EOM) inputs on the evolution of SOC stocks, with a particular focus on the new European targets and the different approaches to calculate them. First, we illustrated through two case-study experiments the different targets set when the SOC stock increase is calculated considering as reference: 1) the SOC stock level at the onset of the experiment and 2) the SOC stock trend in a baseline, i.e., a control treatment without EOM addition. Then, we used 11 long-term experiments (LTEs) with EOM addition in European croplands to estimate the amount of carbon (C) input needed to reach the 0.1 and 0.4% SOC stock increase targets proposed by the Mission Board for Soil Health and Food, calculated with two different approaches. We found that, to reach a 0.1 and 0.4% increase target relative to the onset of the experiment, 2.51 and 2.61 Mg C $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ of additional C input were necessary, respectively. Reaching a 0.1 and 0.4% increase target relative to the baseline required 1.38 and 1.77 Mg C $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ of additional input, respectively. Depending on the calculation method used, the estimated amounts of additional C input required to reach each quantitative target were significantly different from each other. Furthermore, the quality of C input as represented by the C retention rate of the additional organic material (EOM and crop residue), had a significant effect on the variation of SOC stocks. Our work highlights the necessity to take into consideration the additional C input required to increase SOC stocks, especially for soils with decreasing SOC stocks, when targets are set independently of the baseline.

Keywords: soil organic carbon, 4 per 1000, exogenous organic matter, agriculture, Europe 2030 targets, climate change

INTRODUCTION

Land based agricultural activities contribute globally to greenhouse gases (GHG) emissions with approximately 6.2 Gt carbon dioxide equivalents (CO_2eq) each year (including non-food use of agricultural products and excluding emissions associated to land use change) (IPCC, 2019). Improved management practices have the potential to reduce the impact of agriculture on GHG emissions (Smith et al., 1997), and additionally to sequester carbon (C) from the atmosphere through increased soil organic carbon (SOC) stocks (Lal, 2008; Minasny et al., 2017). The potential of agricultural soils to both mitigate climate change and increase food security through improved soil quality [e.g., increased soil fertility and water retention (Lal, 2008)], has been an issue in numerous political agendas for years. It finally gained an international breakthrough in 2015, with the 4 per 1000 initiative proposed at the COP21 (Minasny et al., 2017). The name of the initiative comes from the idea that an increase of SOC stocks of 0.4% (i.e., 4‰) yr^{-1} in the first 30–40 cm of the soil could, at least partially, compensate for the CO_2 emissions from fossil fuel burning. More recently, the Mission Board for Soil Health and Food of the European Union (EU) proposed a series of quantitative targets for European soils to become healthier. Among them, current SOC concentration losses in croplands (calculated in the first 20 cm of the soil from the LUCAS survey as being 0.5% yr^{-1} on average) should be reversed to an increase of 0.1–0.4% yr^{-1} by 2030 (Veerman et al., 2020). It is important to note that SOC concentration losses can result in no changes or even increases in SOC stocks when soil bulk density (BD) increases. Veerman et al. (2020) refer to SOC concentration losses. However, to avoid confusion, we point out that the aimed target in order to have a climate mitigation benefit, should refer to SOC stock increases (i.e., amount of C per hectare).

Management practices that potentially increase SOC stocks include, among others, cover cropping, improved crop rotations, agroforestry systems, converting cropland to grassland, and adding fertilizers and organic amendments to the soil (Chenu et al., 2019; Soussana et al., 2019; Bolinder et al., 2020). Although this latter does not contribute to sequester CO_2 from the atmosphere, adding exogenous organic matter (EOM) can improve soil quality. For instance, through increased water retention and soil fertility (Reeves, 1997; Robertson et al., 2014), EOM may reduce soil erosion and increase crop productivity, indirectly enhancing a virtuous C cycle. That is, by increasing crop productivity, plants' CO_2 fixation is enhanced and higher amounts of crop residue might be left on the soil, increasing the C input and hence the SOC stocks.

Farm-level payments can be used to incentivize the adoption of practices that increase SOC stocks. Payments can be action-based or result-based. Action-based schemes reward farmers for implementing agricultural practices that potentially increase SOC stocks. In contrast, the payment of result-based schemes is contingent upon the achievement of a certain measurable result (European Commission, 2021). Policy makers tend to prefer result-based incentives because the use of funds is more directly linked to the benefit they provide. In this context, it is necessary to set quantitative SOC stock increase targets in order to measure, report and verify the achieved results, and to define a reference against which the SOC stock increase is calculated.

Pellerin et al. (2019) and Soussana et al. (2019) illustrated a 0.4% SOC stock increase target, calculated against a baseline of reference or independently of it, in a set of theoretical examples. On the one hand, setting the target of SOC stocks independently of a baseline, i.e., considering the SOC stocks at the onset of the implementation of an improved practice (that is, at time t_0) as the reference, requires the measurement of SOC stocks only at t_0. However, if SOC stocks are not at steady-state, the rate of increase required to reach the target will depend on the SOC stock trend previous to the implementation of the improved practice (Soussana et al., 2019). In this case, the pressure will be set on soils with degrading SOC stocks, because the rate at which they will have to increase will be higher than soils with stable or increasing stocks (Soussana et al., 2019). On the other hand, increasing SOC stocks relative to a baseline means that the rate of increase to reach the target will be fixed, i.e., independent of the previous SOC stock trend. However, to fix the target it is necessary to collect data on the previous SOC stock trend for at least 5–10 years, which is considered the minimum duration to derive a trend in SOC stocks (Pellerin et al., 2019). For this reason, a large-scale deployment of this latter approach is not straightforward since each SOC storing practice must be associated with a control treatment and this adds complexity to land management.

Topsoil OC stocks are often decreasing in cropland soils in Europe (Goidts and van Wesemael, 2007; Saffih-Hdadi and Mary, 2008; Fernández-Ugalde et al., 2011; Meersmans et al., 2011; Sanderman et al., 2017; Clivot et al., 2019; Veerman et al., 2020). However, opposite examples exist. For instance, SOC stocks (at 15–20 cm depth) are increasing in Swedish cropland due to the presence of more perennial forage crops (Poeplau et al., 2015). In this context, calculating a quantitative target of SOC stocks' increase independently of the baseline seems more appropriate, since it puts the priority on the restoration of degraded soils (Soussana et al., 2019). This is particularly relevant considering the land degradation neutrality (LDN) target of the United Nation Convention to Combat Desertification (UNCCD) (Soussana et al., 2019) and the recently adopted European Green New Deal, which aims to bring the EU (27 countries) to climate-neutrality by 2050.

Although some agricultural practices such as reduced tillage may decrease C outputs from the soil through decreased SOC mineralization rates (Powlson et al., 2012; Haddaway et al., 2016), there is a general consensus that the most efficient way to increase SOC stocks is to increase C inputs to the soil (Virto et al., 2012; Autret et al., 2016; Fujisaki et al., 2018). Increasing SOC stocks independently of the baseline means that additional efforts to increase C inputs will be necessary in soils with decreasing trends. The amount of additional C input required to increase SOC stocks by 0.1 and 0.4% yr^{-1} (as targeted by the Mission Board for Soil Health and Food, Veerman et al., 2020), relative to the baseline or independently from it, has not been quantified yet.

In this study, we estimated the amount of C input required to reach the 0.1 and 0.4% SOC stock increase targets to 20–30 cm

TABLE 1 | Characterization of the control treatments at the long-term experiments (LTEs). Mean annual surface temperature and precipitation were derived from an hourly global climate dataset at 0.5° (GSWP3 http://hydro.iis.u-tokyo.ac.jp/GSWP3/).

Site	Coordinates	Years of experiment	Initial SOC stocks	Carbon input from crops	Mean annual precipitation	Mean annual surface temperature
			Mg C ha^{-1}	Mg C ha^{-1} yr^{-1}	mm yr^{-1}	°C
Champ Noël 3	48.09 °N, 1.78 °W	1990–2008	40.6	1.29	818.1	12.2
Colmar	48.11 °N, 7.38 °E	2000–2013	54.3	2.79	1126.7	9.7
Crécom 3	48.32 °N, 3.16 °W	1986–2008	62	1.84	1150.1	11.8
Feucherolles	48.88 °N, 1.96 °E	1998–2013	39.8	2.22	707.3	11.9
Jeu-les-Bois	46.68 °N, 1.79 °E	1998–2008	48.5	2.99	869.1	12.2
La Jaillière 2	47.44 °N, 0.98 °W	1995–2009	32.4	1.59	794.7	12.8
Le Rheu 1	48.09 °N, 1.78 °W	1994–2009	36.2	1.31	841.2	12.3
Le Rheu 2	48.09 °N, 1.78 °W	1994–2009	36.5	1.03	841.2	12.3
Ultuna	59.82 °N, 17.65 °E	1956–2008	41.7	1.03	541.9*	5.7
Trévarez	48.15 °N, 3.76 °W	1986–2008	115.3	1.94	1314.5	11.9
Avrillé	47.50 °N, 0.60 °W	1983–1991	46.2	2.25	693.8	12
Mean			50.3	1.84	881.7	11.3
Median			41.7	1.84	841.2	12
Minimum			32.4	1.03	541.9	5.7
Maximum			115.3	2.99	1314.5	12.8

From onsite measurements.

depth, calculated with two different approaches, for 11 cropland long-term experiments (LTEs) of additional EOM inputs, located in France and Sweden. We hypothesized that reaching the quantitative targets calculated independently of the baseline would require higher C inputs relative to the same targets calculated against a baseline with decreasing SOC stocks. We also hypothesized that the quality of the EOM would have an impact on the SOC stock change. We used the largely available data on LTEs with EOM treatments as an example that can be expanded to other practices. For other practices such as agroforestry systems or cover cropping, however, one should correct the statistical relationship between C input and SOC stocks, since the C input quality is not the same as for EOM.

MATERIALS AND METHODS

Experimental Sites

We analyzed SOC stock data from 11 long-term cropland experiments in France and Sweden. Each experiment consisted of one control treatment [with or without nitrogen (N) inputs], and one or several treatments of EOM addition (i.e., different types of animal manure, green compost, sewage sludge, peat and sawdust). The total number of treatments with additional EOM was 33, with an average C input from additional organic material of 1.86 Mg C ha^{-1} yr^{-1} (1.46 Mg C ha^{-1} yr^{-1} from EOM inputs and 0.40 Mg C ha^{-1} yr^{-1} from additional crop residue input due to increased crop growth, relative to the control treatment) and a median of 1.84 Mg C ha^{-1} yr^{-1}. The duration of the experiments varied between 9 and 53 years, with an average of 19 years and a median of 16 years (**Table 1**). The experiments were established in the period between 1956 and 2013. EOM inputs were applied at different frequencies and quantities and the evolution of SOC stocks (at 20–30 cm depth) over time relative to a control treatment without any EOM addition was monitored. Plant inputs to the soil were transformed to C input *via* allometric functions, following the *Bolinder* method (Bolinder et al., 2007) and its adaptation to French cropland experiments from Clivot et al. (2019) [see also its application to European cropland experiments in Bruni et al. (2021)]. The *Bolinder* method uses yields' measurements and crop-specific coefficients (i.e., the harvest index and the shoot-to-root ratio), to allocate the C to the aboveground and belowground part of the plant (Bolinder et al., 2007). If not specified otherwise, mean annual surface temperature and precipitation were derived from an hourly global climate dataset at 0.5° (GSWP3 http://hydro.iis.u-tokyo.ac.jp/GSWP3/). Average annual surface temperature of the experiments ranged from 5.7°C (in Ultuna) to 12.8°C (in La Jaillière 2), with an average 11.3°C surface temperature across the sites (**Table 1**). Mean annual rainfall was 881.7 mm across the experiments, with a minimum of 541.9 mm yr^{-1} in Ultuna and a maximum of 1314.5 mm yr^{-1} in Trévarez. The experiments were all under arable use during the study period and, most of them, had a long-term arable history (Levavasseur et al., 2020; Clivot et al., 2019; Kätterer et al., 2011) (for details, see **Supplementary Table S1**). All treatments were rainfed. French sites underwent conventional tillage, with deep ploughing performed almost every year, in addition to some superficial tillage operations (**Supplementary Table S1**). At Ultuna, tillage was performed with a spade at 20 cm depth. Cropping systems were cereal-dominated rotations (*Triticum aestivum*, *Zea mays*, *Hordeum vulgare* and *Avena sativa*) (**Supplementary Table S1**). In particular, three were cereal monocultures of silage *Zea mays* (Champ Noël 3, Le Rheu 1 and Le Rheu 2); four sites had rotations of different cereals (*Triticum aestivum* and silage or grain *Zea mays* in Crécom 3, Feucherolles, La Jaillière 2 and Avrillé); and the other sites rotated cereal crops with root crops (*Beta vulgaris* fodder beet, *Brassica napus* fodder rape and *Brassica napus* Swedish turnip), oilseed crops (*Brassica napus*) and silage

TABLE 2 | Soil properties for the minerally unfertilized and fertilized* control treatments at the beginning of the experiment. More information on the experiments can be found in Clivot et al. (2019), Kätterer et al. (2011), Levavasseur et al. (2020) and Bruni et al. (2021).

	Sampling depth	Bulk density	Clay	Soil C:N	pH
	cm	$g\ cm^{-3}$	%		
Champ Noël 3*	0–30	1.4	15	9	6.3
Colmar	0–28	1.3	23	10.5	8.3
Crécom 3*	0–30	1.4	15	10.2	6.2
Feucherolles	0–29	1.3	16	9.9	6.7
Jeu-les-Bois	0–30	1.5	10	9.7	6.3
La Jaillière 2*	0–30	1.4	21	9	6.8
Le Rheu 1*	0–30	1.3	16	10	5.8
Le Rheu 2	0–30	1.3	14	8.2	6
Ultuna	0–20	1.4	36	8.8	6.2
Trévarez*	0–30	1.5	19	9.5	6
Avrillé	0–30	1.4	18	8.9	6.6

Zea mays. Straw residue was partially or totally incorporated into the soil (**Supplementary Table S1**), except in Ultuna, where all aboveground residues were removed. Champ Noël 3, Crécom 3, La Jaillière 2, Le Rheu 1 and Trévarez received optimal amounts of mineral N fertilizers both in the control and in the EOM treatments, while the other experiments did not receive any N inputs. EOM treatments included: cow manure (12 treatments); 1 treatment where different types of farmyard manure were mixed together; compost (6 treatments, including 2 treatments of biowaste compost, 2 treatments of green manure mixed with sewage sludge, 1 treatment of household waste and 1 treatment of green manure); pig manure (6 treatments, including 2 treatments of composted pig manure and 1 treatment of pig slurry); poultry manure (3 treatments, including one treatment of composted poultry manure); sewage sludge (2 treatments); 1 treatment of straw residue incorporation; 1 peat treatment; and 1 sawdust treatment. Sources of green manure and straw residue, and animal species are specified in **Supplementary Table S1**.

Soil Samples

Soils were sampled between 0–20 and 0–30 cm depth (**Table 2**) in 3–4 replicated plots (plot sizes for each treatment are listed in **Supplementary Table S1**). The SOC stocks were calculated using (**Eq. 1**) (Poeplau et al., 2017):

$$SOC\left(MgC\ ha^{-1}\right) = \mathrm{SOC}(\%) \cdot BD\left(g\ cm^{-3}\right) \cdot sampling\ depth\,(cm) \cdot \left(1 - rock\ fragments\ fraction\ (vol.\%/100)\right), \tag{1}$$

where SOC (%) is soil organic carbon content and BD is the bulk density (**Table 2**). Multiple BD measurements were performed over time at Ultuna, Colmar and Feucherolles. Significant changes of BD with time were found for Ultuna and Feucherolles, while BD remained constant in Colmar and was assumed to be constant for all other sites (i.e., only one measurement of BD was performed). SOC stocks were thus calculated at a fixed soil depth for these sites. Clay content varied between 10 and 36%. Soil pH ranged from 5.8 to 8.3 (**Table 2**).

Statistical Analysis

It is well established that SOC does not accumulate indefinitely but eventually reaches a steady-state (i.e., under constant conditions, C inputs and C outputs eventually outbalance each other and SOC is approximately stable). Hence, SOC accumulation can be represented by an asymptotic curve (Poulton et al., 2018). However, a linear approximation holds well for short periods of time (Arrouays et al., 2002). Since we were studying a relatively short-term period (i.e., 30 years), we analyzed the simulation of SOC stocks' evolution in each treatment with a linear regression (see **Supplementary Figure S1**) and obtained an average coefficient of determination (R^2) of 0.59. This can be written as **Eq. 2**:

$$SOC = m \cdot t + b, \tag{2}$$

Where SOC is the soil organic carbon stock in Mg C ha^{-1}, m is the slope coefficient, b the intercept, t is time (i.e. the number of years since the beginning of the experiment).

We evaluated the effect of total C input on the evolution of SOC stocks, calculated with two approaches (T_0 and B, see **Eqs 4**, **5**). We used a linear mixed effect model, with an interaction effect between the quantity and the quality of the total C input. The quality was expressed through the C retention coefficient of the exogenous C input, which represents the proportion of exogenous C that is incorporated into SOC and is not mineralized within 1 year. Values for the C retention coefficient were taken from Levavasseur et al. (2020) and Clivot et al. (2019) for each EOM and crop type (**Supplementary Table S1**). The authors derived this coefficient by optimizing the "h" parameter of the AMG model, a multi-compartmental SOC model that simulates the dynamics of SOC (Andriulo et al., 1999). Parameter "h" was derived by fitting time series of differences in SOC stocks between EOM treatments and controls (Levavasseur et al., 2020). Thus, the C input quality factor (i.e., the C retention coefficient) expresses numerically the quality of the crop species and EOM input of the treatment. Since C input in each treatment came from multiple sources with different C retention coefficients (i.e., aboveground plant material, belowground plant material and EOM inputs), $C_{quality}$ was calculated as the weighted average of the C retention coefficients between the different sources of C input in the treatment. We assumed that the explanatory variables, i.e., C input quantity and C retention coefficient had fixed effects, while the experimental site was set to have a random effect. This eliminates the spatial correlation among treatments carried out at the same site. Model parameters were estimated by maximizing an approximation to the likelihood integrated over the random effect, as in **Eq. 3**:

$$SOC\text{ increase}_i\ (\%) = a_0^{site} + a_1 \cdot C_{quantity} + a_2 \cdot C_{quality} + a_3 \cdot C_{quantity} \cdot C_{quality} + \varepsilon, \quad (3)$$

With $i = T_0\ or\ B$ (i.e., SOC stock increase calculated with T_0 or B approaches, see *Calculating a 0.1 and 0.4% Soil Organic Carbon Stock Increase Target* section). And where: a_0^{site} is the site-dependent intercept of the regression; a_1 and a_2 are the coefficients of the main factors, i.e., the quantity of total C input ($C_{quantity}$) and the C retention coefficient ($C_{quality}$), respectively; a_3 is the coefficient of the interaction effect between $C_{quantity}$ and $C_{quality}$; and ε is the error term of the linear mixed effect model ($\varepsilon \tilde{} N\ (0, \sigma^2)$) (and not of standard error propagation).

To test the significance of differences between C input quantities to reach the 0.1 and 0.4% targets (calculated with T_0 or B approaches) at the experimental sites, one-way ANOVA combined with post-hoc tests (Bonferroni) and Student's t tests were applied. Normal distribution of the data was tested with a Shapiro-Wilks normality test.

Calculating a 0.1 and 0.4% Soil Organic Carbon Stock Increase Target

The increase of SOC stocks can be calculated 1) relative to the value of the SOC stocks at the onset of the study period (i.e. at t_0) or 2) relative to a baseline, i.e., the SOC stock trend of a control treatment. Assuming that we want to increase SOC stocks by 0.1% or 0.4% each year, the first approach (T_0) can be written as **Eq. 4**:

$$SOC_{T_0} = \mathrm{SOC}_0^{control} \cdot (1 + \text{target} \cdot n), \quad (4)$$

Where SOC_{T_0} is the amount of SOC stock targeted by the T_0 control approach, $\mathrm{SOC}_0^{control}$ is the SOC stock in the control treatment at t_0, target = 0.001 or 0.004, for a 0.1 and 0.4% SOC stock increase, respectively, and n is the number of years for which the SOC increase is estimated. Assuming SOC stocks evolve linearly with time, the second baseline approach (B) to calculate a 0.1% or 0.4% SOC stock increase target is equal to **Eq. 5**.

$$SOC_B = \mathrm{SOC}_0^{control} \cdot \left(1 + \left(relative\_slope^{control} + \text{target}\right) \cdot n\right), \quad (5)$$

Where SOC_B is the target set by the baseline approach, $relative\_slope^{control} = \frac{m}{\mathrm{SOC}_0^{control}}$, with m being the slope coefficient of the regression line of the SOC stocks in the control treatment (see **Eq. 2**), For the rest of the study, the predicted SOC stocks will be evaluated over 30 years, i.e., $n = 30$. Annual average CO_2 fluxes are calculated for the control treatments, converting annual SOC stock changes (Mg C ha^{-1}) to CO_2 equivalents (Mg CO_2eq) with the coefficient 44/12. Potential average annual CO_2 fluxes are also calculated for virtual treatments that would allow to reach the 0.1 and 0.4% targets (with approaches T_0 and B) through CO_2 storage practices. Thus, negative values represent net CO_2 emissions from the soil to the atmosphere, while positive values indicate potential CO_2 storage in the soil.

RESULTS

Effect of the Target Calculation Approach: Two Case Studies

We applied the two approaches described above (i.e., **Eq. 4** for T_0 and **Eq. 5** for B) to two case study LTEs with very different SOC stock dynamics in their control treatment, to illustrate how different SOC stock increase targets are set. The first case study was the 23 years old experiment Crécom 3, where SOC stocks in the first 30 cm are approximately at steady-state (**Figure 1A**) (i.e., over time, fresh C inputs to the soil compensate SOC losses by decomposition and SOC stocks can be approximated with a constant line). This site, located in northwestern France, has a control treatment with an annual SOC stock change of −0.06% (correlation coefficient of the regression line between SOC stocks and time, $R^2 = 0.04$). The slope coefficient of the correlation between SOC stocks and time in the control treatment was −0.038 ± 0.125 (mean ± standard error, SE) (**Table 3**). The second site Feucherolles was a 16 years old northcentral French experiment. At the control treatment, SOC stocks at 29 cm depth were decreasing with a strong relative annual change of −0.65% ($R^2 = 0.65$) (**Figure 1B**).

The Importance of Considering the Baseline

In **Figure 1**, we illustrate the theoretical SOC stock increase imposed by a 0.4% target calculated with T_0 (**Eq. 4**) (blue colored area) and B (**Eq. 5**) (orange colored area). Outcomes are different whether the control treatment's trend is at steady-state (**Figure 1A**) or not (**Figure 1B**). If SOC stocks in the control treatment are approximately stable (e.g., Crécom 3), calculating the 0.4% increase with **Eqs 4** or **5** sets similar targets of SOC stock increases. In both cases, the SOC stocks after 30 years of implementation of the storing practice have to be higher than the initial SOC stock level. If SOC stocks in the control treatment are not at steady-state (**Figure 1A**), the two approaches result in different SOC stock increase targets. If SOC stocks are decreasing, we can see from **Figure 1B** that the target based on B allows increasing SOC stocks relative to the control treatment. However, SOC stocks are still decreasing (though at a weaker rate than the baseline, since the SOC stock target increase was set against the baseline).

To summarize, B (relative to the baseline) sets fixed targets for soils with decreasing, stable or increasing SOC stocks, but does not guarantee to have a net increase of SOC stocks after *n* years. On the contrary, T_0 (relative to SOC stocks at t_0) imposes both stable and decreasing SOC stocks to increase (accruing SOC stocks have to increase only if their rate of increase is lower than the target rate). However, in this case, soils with decreasing SOC stocks have to increase at a much higher rate. Note that we showed the theoretical results for two case studies for illustrative purposes. However, these results are generalizable to any soil with stable or decreasing SOC stocks that can be approximated with a linear regression (**Appendix A**).

Supplementary Table S2 shows the predicted annual average CO_2 fluxes at the control treatments of all the 11

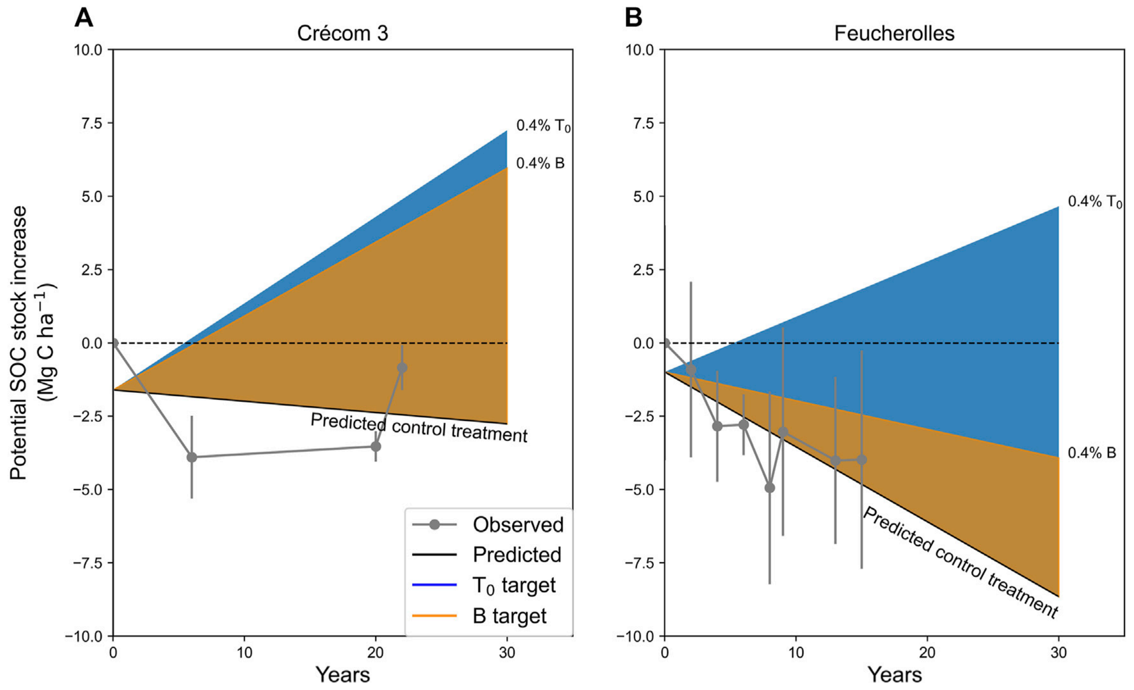

FIGURE 1 | Theoretical soil organic carbon (SOC) stock evolution needed to reach an average annual 0.4% SOC stock increase for 30 years, based on two calculation methods (T_0 and B, calculated with **Eq. 4** and **Eq. 5**, respectively) for **(A)** Crécom 3 and **(B)** Feucherolles (detailed demonstration available in **Appendix A**). Observed SOC stocks (at 0–30 and 0–29 cm depth, respectively) and predicted SOC stocks (with a linear regression) for the control treatments are normalized against initial SOC stocks.

TABLE 3 | Predicted coefficients of the linear regressions of soil organic carbon (SOC) stock changes with time, for the Crécom 3 (0–30 cm) and Feucherolles (0–29 cm) control treatments.

		Predicted coefficients	Standard error	t statistics	*p* Value	Confidence interval (95%)	
Crécom 3	Intercept	60.3944	1.897	31.831	0.001	52.231	68.558
	Slope	−0.0385	0.125	−0.308	0.787	−0.577	0.5
Feucherolles	Intercept	38.7868	0.658	58.991	0	37.178	40.396
	slope	−0.2553	0.076	−3.349	0.015	−0.442	−0.069

experimental sites, considering SOC stock changes over 30 years relative to t_0, and the potential annual average CO_2 fluxes at the virtual treatments that would allow to reach the 0.1 and 0.4%, T_0 and B targets, over 30 years. We can see that all control treatments were emitting CO_2 to the atmosphere (1.63 ± 0.73 Mg CO_2eq ha^{-1} yr^{-1} emitted on average ± standard deviation, SD), over the predicted 30 years of experiment. Reaching virtual targets 0.1% T_0 and 0.4% T_0 would theoretically allow to store CO_2 in the soil at every site (0.18 ± 0.07 Mg CO_2 eq ha^{-1} yr^{-1} and 0.73 ± 0.29 Mg CO_2 eq ha^{-1} yr^{-1} stored on average ± SD, respectively). On the contrary, targets 0.1% B and 0.4% B would theoretically keep emitting CO_2 at all sites (1.45 ± 0.72 Mg CO_2eq ha^{-1} yr^{-1} and 0.90 ± 0.72 Mg CO_2 eq ha^{-1} yr^{-1} emitted, respectively), except at Crécom 3, where 0.08 Mg CO_2 eq ha^{-1} yr^{-1} and 0.75 Mg CO_2 eq ha^{-1} yr^{-1} would be stored on average, if targets 0.1% B and 0.4% B were reached, respectively (**Supplementary Table S2**).

Temporal Changes in Topsoil Organic Carbon Stocks at the Long-Term Experiments

Concerning all the 11 LTEs, in the control treatments SOC stocks were decreasing by 0.98 ± 0.47% yr^{-1} (mean ± SD) on average (i.e., −0.44 ± 0.20 Mg C ha^{-1} yr^{-1}, mean ± SD). The average R^2 of the linear regressions between SOC stocks and time in the control treatments was 0.64. The SOC stocks in the additional C input treatments were increasing by 0.17 ± 1.35% yr^{-1} on average (i.e., 0.07 ± 0.56 Mg C ha^{-1} yr^{-1}, R^2 = 0.57). Predicted SOC stocks after 30 years are shown in **Table 4**, together with the 0.1 and 0.4% SOC stock targets

TABLE 4 | Predicted soil organic carbon (SOC) stocks (Mg C ha^{-1}) of the experimental sites.

Sites	SOC stock t_0 control treatment	SOC stock t_{30} control treatment	SOC stock t_{30} at T1	SOC stock t_{30} at T2	SOC stock t_{30} at T3	SOC stock t_{30} at T4	SOC stock t_{30} at T5	SOC stock t_{30} at T6	SOC stock 0.1% T_0 target	SOC stock 0.1% B target	SOC stock 0.4% T_0 target	SOC stock 0.4% B target
Champ Noël 3	39.2	28.3	30.1						40.4	29.5	43.9	33.0
Colmar	53.4	40.9	56.5	43.9	51.2	56.0	53.2		55.0	42.5	59.8	47.3
Crécom 3	60.4	59.2	70.0	36.1					62.2	61.1	67.6	66.5
Feucherolles	38.8	31.1	82.5	82.7	63.4	60.4			40.0	32.3	43.4	35.8
Jeu-les-Bois	48.5	29.1	63.4	59.3	53.1				50.0	30.6	54.4	34.9
La Jaillière 2	33.1	18.9	25.0	22.4	17.0	26.6	24.0	17.9	34.1	19.9	37.1	22.9
Le Rheu 1	38.2	20.9	24.7						39.4	22.1	42.8	25.5
Le Rheu 2	37.4	18.0	23.2	29.9					38.5	19.2	41.9	22.5
Ultuna	42.1	35.5	44.9	46.7	73.5	55.6	50.6	71.7	43.4	36.8	47.2	40.6
Trévarez	108.2	86.8	94.7	100.2					111.4	90.1	121.2	99.8
Avrillé	46.7	30.3	37.3						48.1	31.7	52.4	35.9

*t_0 and t_{30} indicate the 0th and the 30th year of the prediction, respectively. T1, T2, . . . , T6 indicate the exogenous organic matter (EOM) treatments' identification code for each site (detailed description of the EOM treatments are provided in **Supplementary Table S1**). The target SOC stock level was calculated for a 0.1 and 0.4% average annual increase over 30 years, based on approach T_0 and B.*

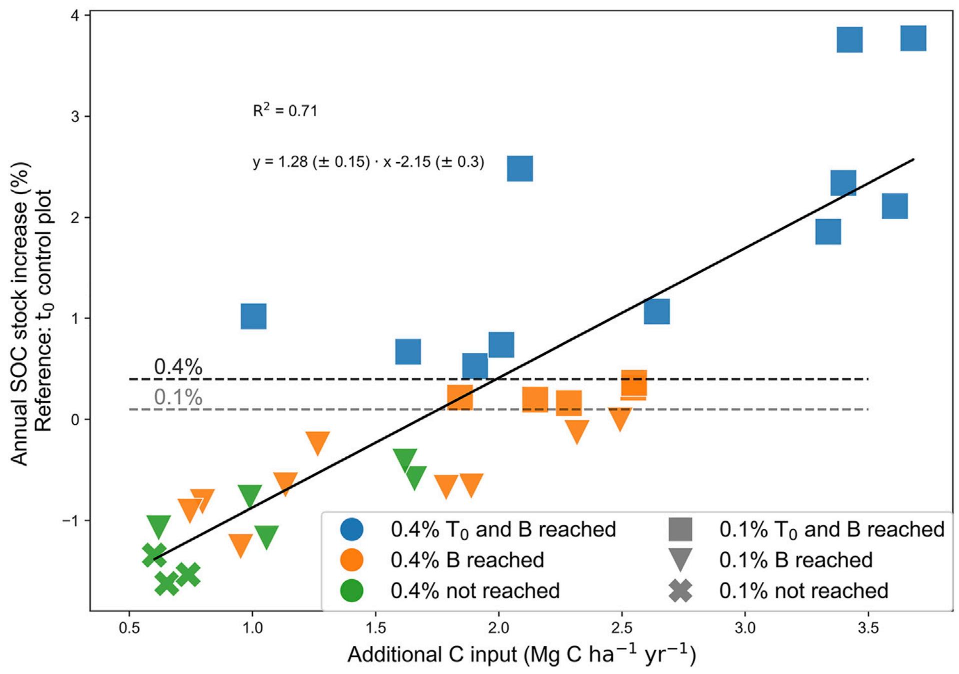

FIGURE 2 | Correlation between annual soil organic carbon (SOC) stock increase (%) (at 20–30 cm depth) and additional carbon (C) input in the exogenous organic matter (EOM) treatments (Mg C ha^{-1} yr^{-1}). Different colors indicate whether the 0.4% SOC stock increase target was reached, based on the different approaches used to calculate the target (blue indicates that both 0.4% T_0 and 0.4% B targets were reached, orange indicates that 0.4% B was reached and green indicates that no 0.4% target was reached). Different symbols indicate whether the 0.1% SOC stock increase target was reached, based on the different approaches used (squares indicate that both 0.1% T_0 and 0.1% B targets were reached, inverse triangles indicate that 0.1% B was reached and crosses indicate that no target was reached). SOC stock increase was calculated relative to the first year of experiment in the control treatment. Additional C input consisted of EOM inputs and additional C from increased crop growth, relative to the control treatment.

calculated with **Eq. 4** (T_0) and **Eq. 5 (B)**. Overall, almost 50% of treatments increased SOC stocks by at least 0.1%, compared to the initial level of SOC stock (T_0) and more than 90% of treatments increased SOC stocks by at least 0.1% compared to the baseline (B) (**Table 4**). 33% of C input treatments increased SOC stocks by at least 0.4% yr^{-1} (T_0) and 76% of treatments increased SOC stocks by at least 0.4% yr^{-1} (B) (**Table 4**). Since SOC stocks in all control treatments were

TABLE 5 | Amount of additional carbon (C) input (Mg C ha^{-1} yr^{-1}) (relative to the C input in the control treatment) that increased soil organic carbon (SOC) stocks by 0.1 and 0.4% yr^{-1} on average for 30 years, according to T_0 and B. Additional C input refers to exogenous organic matter (EOM) inputs plus C input from increased crop growth relative to the control treatment.

Statistics	Additional C input	Target					
		0.1%			0.4%		
		T_0	B	Not reached	T_0	B	Not reached
Min	Mg C ha^{-1} yr^{-1}	1.0	0.62	0.60	1.0	0.75	0.6
Max	Mg C ha^{-1} yr^{-1}	3.68	2.49	0.74	3.68	2.55	1.66
Mean	Mg C ha^{-1} yr^{-1}	**2.51**	**1.38**	**0.66**	**2.61**	**1.77**	**0.99**
SD	Mg C ha^{-1} yr^{-1}	0.19	0.15	0.03	0.27	0.17	0.14

Bold values indicate mean additional C input levels.

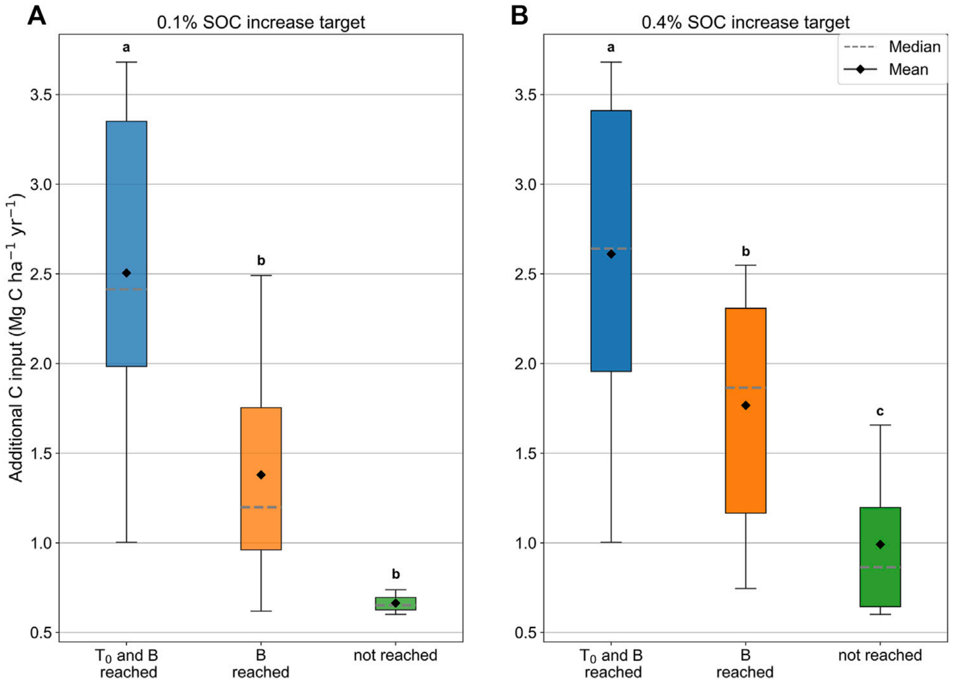

FIGURE 3 | Additional carbon (C) input (Mg C ha^{-1} yr^{-1}) relative to the control treatment for groups of treatments where: **(A)** 0.1% T_0 and B targets were reached or not, **(B)** 0.4% T_0 and B targets were reached or not. Boxes extend from the lower to the upper quartile values of the data, with a line at the median and a spot at the mean. Whiskers show the range of the data and points past the end of the whiskers are flier points. Groups within the same panel with different lowercase letters are significantly different ($p \leq 0.05$) from each other.

decreasing or approximately stable, treatments that met the T_0 target also reached target B. Overall, almost 10% of EOM treatments did not reach any increase target.

Amount of Additional Carbon Input Needed to Reach the 0.1 and 0.4% Soil Organic Carbon Stocks Increase Targets

The increase in SOC stocks at 20–30 cm depth was positively correlated to the additional C input from EOM and increased crop growth ($R^2 = 0.71$) (**Figure 2**). **Figure 2** shows the relationship between additional C input and SOC stock increase, highlighting the levels of C input in the treatments where the 0.1 and 0.4% targets were reached, according to T_0 and B. **Table 5** shows the additional C input in the treatments where both the 0.1 and 0.4% increase target were reached, or not. We found that the amount of additional C in the group of treatments that reached a 0.1% T_0 target was significantly different ($p \leq 0.05$) from the group that reached a 0.1% B target (**Figure 3**). However, the average amount of additional C input in the group of treatments that reached a 0.1% B target was not significantly different from the average amount of additional C in the group of treatments where no 0.1% target was reached. Concerning the 0.4% increase target, all groups of treatments were different from each other at a significant level of 0.05 (**Figure 3B**). Treatments where the 0.4% T_0 target was reached, had between 1.0 and 3.68 Mg C ha^{-1} yr^{-1} inputs (EOM plus additional inputs due to enhanced crop growth relative to the control treatment), with an average of 2.61 ±

TABLE 6 | Results of the linear mixed effect model of **Eq. 3**.

	SOC stock variation (T_0)			SOC stock variation (B)		
	Predicted coefficients	Standard error	*p* Value	Predicted coefficients	Standard error	*p* Value
Intercept	3.51	1.79	0.059	2.57	1.84	0.1726
$C_{quality}$	−14.64	4.65	0.0037	−9.03	4.80	0.0697
$C_{quantity}$	−1.82	0.58	0.0039	−1.24	0.60	0.0484
Interaction effect	6.19	1.48	0.0002	4.49	1.53	0.0064

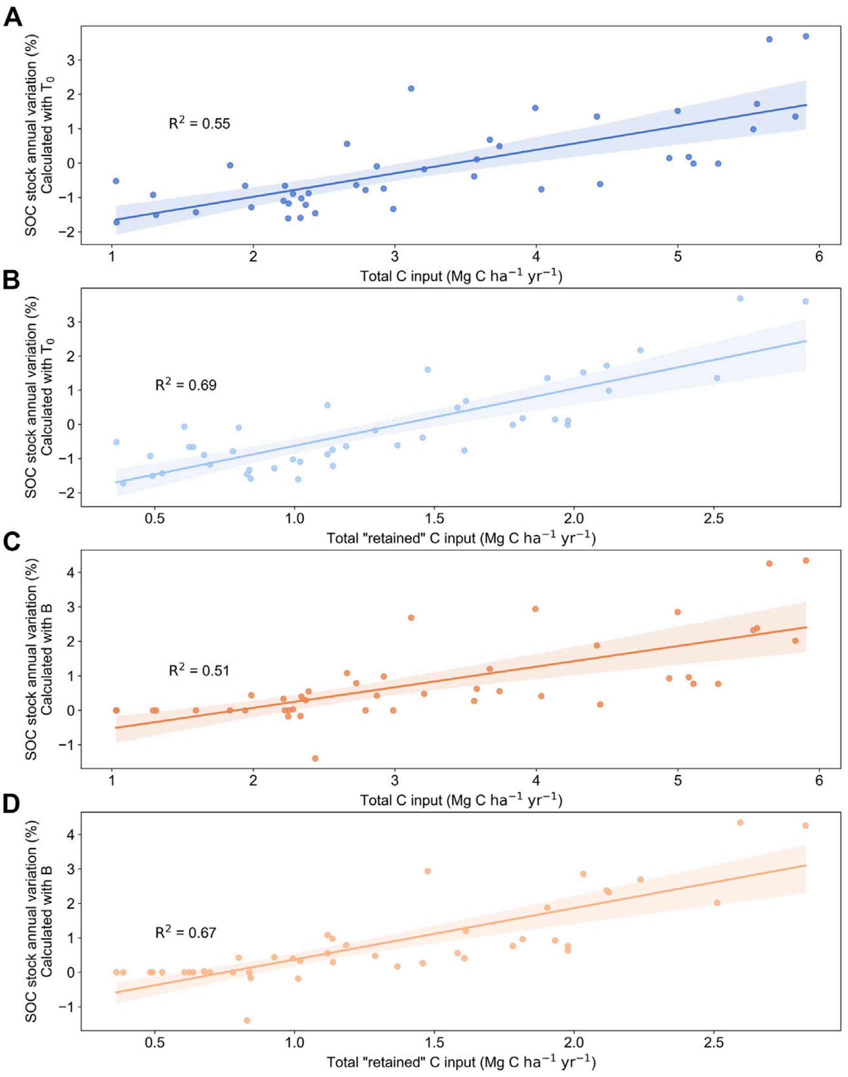

FIGURE 4 | Relationship between soil organic carbon (SOC) stock annual variation (%) and 1) total carbon (C) input (Mg C ha^{-1} yr^{-1}) [panel **(A)** and **(C)**]; 2) retained C input (Mg C ha^{-1} yr^{-1}) [panel **(B)** and **(C)**]. Retained C inputs were calculated as the total C input, multiplied by the C retention coeffcient for each C input quality (**Supplementary Table S1**). The SOC stock annual variation was calculated with T_0 [panel **(A)** and **(B)**] and with B [panel **(C)** and **(D)**].

0.27 Mg C ha^{-1} yr^{-1} (mean ± SE) (**Table 5**). To reach a 0.1% T_0 target, 2.51 ± 0.19 Mg C ha^{-1} yr^{-1} were sufficient. Treatments that reached the 0.4% B target had 1.77 ± 0.17 Mg C ha^{-1} yr^{-1} inputs on average, while treatments that reached the 0.1% B target had 1.38 ± 0.15 Mg C ha^{-1} yr^{-1} inputs. Treatments that reached the B target had a high variability of C input, i.e., between 0.75 and 2.55 Mg C ha^{-1} yr^{-1} for a 0.4% B target and between 0.62 and 2.49 Mg C ha^{-1} yr^{-1} for a 0.1% B target (**Table 5**). Treatments where no target was reached had 0.66 ± 0.03 Mg C ha^{-1} yr^{-1} inputs on average. C input in these treatments ranged between 0.60 and 0.74 Mg C ha^{-1} annually (**Table 5**). Considering EOM only, the necessary average C input was: 1.95 ± 0.10 Mg C ha^{-1} yr^{-1} to reach a 0.4% T_0 target, 1.84 ± 0.11 Mg C ha^{-1} yr^{-1} to reach a 0.1% T_0 target, 1.38 ± 0.11 to reach a 0.4% B target, and 1.16 ± 0.09 to reach a 0.1% B target.

Effect of the Quality of Carbon Input on the Variation of Soil Organic Carbon Stocks

We found that the quantity of C input and the quality of C input (i.e., the C retention coefficient) both had an effect on the increase of SOC stocks ($p \leq 0.05$), when this was calculated relative to t_0 (T_0) (**Table 6**). We also found that there was a significant interaction effect between $C_{quantity}$ and $C_{quality}$, meaning that the effect of $C_{quantity}$ depended on the value of the $C_{quality}$ and vice versa (**Table 6**). This interaction was also significant when the SOC stock increase was calculated relative to the baseline in the control treatment (B). But in this case, while the C input quantity had a significant effect, no main significant effect of the C retention coefficient was found (**Table 6**). **Figure 4** shows the relationship between annual SOC stock variation and: 1) total C input in all treatments (**Figures 4A,C**) and 2) total C input multiplied by the C retention coefficient in all treatments (**Figures 4B,D**). The annual SOC stock variation was calculated against the initial SOC stock in the control treatment or against the baseline. We can see that, when the C retention coefficient is taken into account, the R^2 between annual SOC stock variation and C input slightly improves (from 0.55 to 0.69 when the variation of SOC stocks is calculated with T_0 and from 0.51 to 0.67 when the variation of SOC stocks is calculated with B).

DISCUSSION

Reaching Targets of Soil Organic Carbon Stock Increase to 20–30 cm Depth

We compared two approaches to calculate the increase of SOC stocks. One, where the control was the SOC stock at the onset of the experiment (**Eq. 4**), and one, where the control was the trend of the SOC stocks in the control treatment (**Eq. 5**). Both can be used to set quantitative targets for the implementation of SOC stock increasing practices, in the context of result-based incentives. The two case studies of Crécom 3 and Feucherolles illustrated that the two approaches set different targets, depending on the initial state of the SOC stocks due to previous practices. In particular, if SOC stocks are declining in the control treatment, a target calculated against a baseline (B), might not be sufficient to induce a net positive SOC storage after implementation of the improved practice. In contrast, the T_0 target will guarantee decreasing SOC stocks to reverse their trend. However, reaching such target requires the implementation of practices that supply sufficient levels of additional C input (e.g., from EOM and crop residue inputs).

Note that, in **Supplementary Table S2**, we provided the potential annual average CO_2 storage rates, in case any of the targets were reached, over 30 years, at the 11 LTEs. However, this supposes that the improved management practice contributes to CO_2 sequestration (e.g., by enhancing photosynthesis *via* the introduction of cover cropping or agroforestry systems). In fact, adding EOM inputs to the soil does not sequester CO_2 from the atmosphere, since EOMs contain C that was already fixed and is only redistributed elsewhere. Nonetheless, many authors have shown that adding EOM inputs to the soil does increase SOC stocks (e.g., Maillard and Angers, 2014; Li et al., 2021). Hence, C from this atmospheric CO_2 fixation will still be sequestered in soils for a given time period. In the 11 LTEs studied, the majority of EOM input treatments increased SOC stocks by 0.1 and 0.4% yr^{-1} on average for 30 years, relative to the baseline situation where no additional EOM was added to the soil (target B). However, we found that the increase of SOC stocks from additional EOM treatments was not sufficient to reach a 0.1% or 0.4% SOC stock target relative to the initial SOC stocks after 30 years (target T_0), unless very high amounts of C input were added to the soil. That is, 2.51 Mg C ha^{-1} yr^{-1} for a 0.1% T_0 target and 2.61 Mg C ha^{-1} yr^{-1} for a 0.4% T_0 target over 30 years, considering total additional C input, and 1.84 and 1.95 ± 0.11 Mg C ha^{-1} yr^{-1}, respectively, considering EOM inputs only. This is in line with Poulton et al. (2018), who found that with similar high amounts of additional C input, SOC stocks increased more than 0.4% yr^{-1} relative to their value at t_0 at several LTEs in the UK.

Additionally, we found that the quality of the C input, as expressed by its C retention coefficient, had a main significant effect on the SOC stocks' increase only when this was calculated against t_0. This is probably due to the lower target set by B, and because almost any quantity of EOM input increased SOC stocks compared to a reference situation where SOC stocks were decreasing (see **Table 4**). However, we found that the interaction effect between C input quantity and quality was significant for both calculation approaches. This means that not only the quantity but also the quality of the C input has a significant effect on the SOC stock increase. The relevance of adequately determining the mineralization and C retention coefficients of EOMs for accurate estimations of their long-term effects on soil fertility and SOC stocks is well known, as recently summarized by Levavasseur et al. (2022). The work from Levavasseur et al. (2022) provides evidence from controlled laboratory experiments that some sources of EOM after application remain in soils in higher proportions over time. For example, they found that composts generally had a lower C mineralization rate compared to other EOMs, such as sewage sludges and animal residues (e.g., animal manures and anaerobic digestates) (Levavasseur et al., 2022). That is, on average only 33% of added composts were mineralized within 1 year, while the fraction of readily mineralized EOM in the first year was: 34% for digestates, 52% for livestock manures and 50% for sewage sludges. This can be expected since the composting process converts biodegradable organic matter into more stable organic materials.

The evolution of the retained C input with time (i.e., the amount of C input multiplied by its associated C retention coefficient over time), together with the evolution of the measured and predicted SOC stocks over the experiments' length can be found in **Supplementary Figure S2**, for each treatment. Because the number of SOC stock measures in time was small in the majority of the treatments, it was not possible to assess correctly the cross-correlation between retained C input and measured SOC stocks with time. Using the predicted SOC stocks (see **Eq. 2**) instead of measured SOC stocks, we found that the average R^2 between retained C input and predicted SOC stocks was 0.17. While our results suggested that the average SOC stock change rates depended on the quality of the C input, more experiments with frequent SOC stock measures would be needed to assess the temporal effect of the quality of C input on SOC stocks. More frequent SOC stock measures would also allow to predict SOC stock trends with more reliability and avoid overfitting the data. This was the case in Crécom 3 T2 and Jeu-les-Bois treatments, where only two measures of SOC stocks with time were available. Furthermore, a higher number of treatments with similar qualities of C input would be necessary to assess the effect of "categories" of C inputs (e.g., cow manures, composted cow manures and sewage sludges) on SOC stocks.

Reaching the 0.1 and 0.4% Targets in European Croplands

The Mission Board for Soil Health and Food (Veerman et al., 2020) reported that 23% of European soils have low SOC concentration and declining SOC stocks in the top 20 cm, almost all being under agricultural use. Panagos et al. (2020) estimated that arable land has experienced a SOC stock loss, at the same depth, of about 0.06% between 2009/2012 and 2015 (LUCAS JRC). This loss amounts to 0.5% yr^{-1} in soils that were under cropland at both survey dates (i.e., 2009/2012 and 2015), with a large variability of the SOC stock variation across the database (Hiederer, 2018; Veerman et al., 2020). In the LTEs analyzed here, SOC stocks in the control treatments (including both fertilized and unfertilized controls) were decreasing on average by 0.98 ± 0.47% yr^{-1}, which is similar to the average situation of SOC stocks in European cropland soils. The Mission Board for Soil Health and Food aims to improve the health of 75% of European soils by 2030. In particular, the current SOC losses in cropland soils are expected by the Mission Board for Soil Health and Food to be reversed to an increase of 0.1–0.4% yr^{-1} by 2030, compared to current SOC levels. This is equivalent to setting an increase target calculated against t_0 (T_0). Here, we showed that, at the plot scale, the necessary increase of C input depends both on the calculation method used to set the targets, and on the quality of the C input. Although the control treatments in the 11 LTEs analyzed have similar SOC stock trends as the average cropland soils in Europe, observations from two European countries cannot be extrapolated to entire Europe. However, our analyses show that, even considering relatively similar pedo-climatic conditions, the amounts of C input required to reach quantitative targets of SOC stock increase were significantly different from each other, depending on the approach used to calculate these targets. These results are important for policy makers who may want to implement adequate subsidies, depending on specific soil conditions and targets aimed.

It is important to note that we used EOM treatments as a study case, since we had access to data from 11 LTEs where SOC stocks (at 20–30 cm depth) and C input were monitored, over 9–53 years. However, large scale additional increases in SOC stocks through EOM management in Europe are unlikely because EOM are already applied to soils (Foged et al., 2011; Zhang et al., 2017; Soussana et al., 2019). Moreover, although EOM inputs improve soil fertility and soil health, they are not *per se* a climate mitigation measure. In fact, adding EOM inputs to the soil does not sequester additional CO_2 from the atmosphere but it redistributes spatially C that is already fixed and can be stabilized in the soil. In the experiments analyzed, EOM inputs were spread on the soil surface. Hence, the major effects on SOC stocks can be expected in topsoil layers. Although there might be an impact of the addition of EOM inputs at deeper soil layers because of advection or bioturbation processes, deeper soil layers were not considered because data on the biological activity or on deeper SOC were not available.

Our results, together with the recent work from Levavasseur et al. (2022), show that the quality of the additional C input is critical to increase SOC stocks. Strategies to enhance SOC stocks should increase the quality of the EOM brought to soils, as well as redistributing EOMs from lands with high EOM inputs to croplands that do not have sufficient EOMs (Asai et al., 2014; Aillery et al., 2018). The cost associated to the transportation of EOMs is often a limit to the distance at which they are commuted. A study from Asai et al. (2014) reported that the maximum distance covered from the majority of farmers involved in manure exchange in Denmark ranged between 1 and 5 km. Although the distance was higher for organic farmers, the majority of them still hauled less than 10 km. Also, transporting EOM induces GHG emissions that might offset the benefits of increased SOC stocks.

Our results show that SOC stock increase targets in cropland soils might be feasible using sufficient amounts of C input (i.e., between 1.38 and 2.61 $Mg\,C\,ha^{-1}\,yr^{-1}$ on average, according to the 11 LTEs analyzed, and depending on the calculation method used) and supposing that SOC variations are linearly controlled by C input. Such linear relationships remain to be established for other agricultural practices that provide additional C input to the soil, such as cover crops, improved crop rotations, temporary leys and agroforestry (Soussana et al., 2019). For instance, Cardinael et al. (2018) estimated that, in an agroforestry system in Southern France, 2.73 additional $Mg\,C\,ha^{-1}\,yr^{-1}$ from vegetation, litterfall, and crop residues increased SOC stocks by 0.45% yr^{-1} for 18 years up to 30 cm depth, compared to an agricultural control treatment. This is similar to our results with EOM treatments in the first 20–30 cm depth, suggesting that a 0.4% target might be feasible with the implementation of other practices, such as agroforestry systems. To predict with more confidence the potential of different qualities of C input to increase SOC stocks, other LTEs with such practices should be considered. For example, Wiesmeier et al. (2020) identified cover cropping and agroforestry systems as the practices with the highest potential to increase SOC stocks up to 40 cm depth in Bavaria, compared to current land management. However, they estimated that a 0.4% SOC stock increase target was not possible in that region.

CONCLUSION

In the 11 cropland LTEs analyzed, reaching quantitative targets of SOC stock increase required significantly different amounts of additional C input, whether the targets were calculated against the initial level of SOC stocks or against a baseline practice (i.e., a control treatment with or without mineral fertilizer inputs and without any EOM, where SOC stocks were mainly decreasing). Incentives to implement agricultural practices that increase SOC stocks should take into consideration that higher C inputs are required for soils with decreasing SOC stocks, if quantitative targets of SOC stock increase are calculated regardless of the current SOC stock trends. Since EOM inputs are already widely applied in European croplands, future works should analyze the effect of C input on SOC stocks in LTEs, considering the implementation of other practices (e.g., agroforestry systems and cover cropping, which are also able to sequester additional CO_2 from the atmosphere). Strategies to implement a portfolio of agricultural practices that allow increasing SOC stocks should be considered to reach the Mission Board for Soil Health and Food's targets by 2030.

DATA AVAILABILITY STATEMENT

Data owners maintain and can access the data. Requests to access these datasets should be directed to them (i.e. Thomas Kätterer for Swedish experiment and Annie Duparque for French experiments).

AUTHOR CONTRIBUTIONS

EB performed the calculations and prepared the manuscript with contributions from all co-authors. HC, TK, IV, and MM provided the data.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.824724/full#supplementary-material

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APPENDIX A GENERALIZATION OF THE TARGETS' COMPARISON

Demonstration that T_0 target is always higher than B target if SOC stocks in a control treatment are decreasing and approximated with a linear regression.

Imagine that a control treatment can be approximated by a linear regression. Then, it can be written as **Eq. A1**:

$$\mathrm{SOC}^{control} = m^{*}t + \mathrm{SOC}_0^{control} \tag{A1}$$

Where: $\mathrm{SOC}^{control}$ are the soil organic carbon stocks in the control treatment, t is time (i.e., the number of years since the beginning of the experiment), m is the slope of the regression line and $\mathrm{SOC}_0^{control}$ are the SOC stocks at t = 0.

The relative slope (i.e., the slope of the SOC stocks, relative to the first year of SOC stocks in the control treatment) can be written as **Eq. A2**:

$$relative\_slope^{control} = \frac{m}{\mathrm{SOC}_0^{control}} \tag{A2}$$

If we suppose that the control treatment has a decreasing SOC stock trend, this means that the slope (m) is negative, hence the $relative\_slope^{control}$ is negative too.

From **Eqs 4**, **5** we derive the targets set, based on T_0 (i.e., SOC_{T_0}) and B (i.e., SOC_B), respectively. We calculate the difference between SOC_{T_0} and SOC_B ($SOC_{T_0} - SOC_B$). That is, the difference between **Eq. 4** and **Eq. 5**. With a few simple computations, we derive **Eq. A3**:

$$SOC_{T_0} - SOC_B = -\mathrm{SOC}_0^{control} \cdot n \cdot relative\_slope^{control} \tag{A3}$$

Since $\mathrm{SOC}_0^{control} > 0$, $n > 0$ and $relative\_slope^{control} < 0$, $SOC_{T_0} - SOC_B > 0$. Hence, $SOC_{T_0} > SOC_B$.

Similarly, we can demonstrate that T_0 target is equal to B target if SOC stocks in the control treatment are at steady-state and approximated with a linear regression.

If SOC stocks are at steady-state, $m = 0$. Hence, $SOC_{T_0} = SOC_B$.