



On-Farm Relationships Between Agricultural Practices and Annual Changes in Organic Carbon Content at a Regional Scale

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Both soil quality degradation and climate change mitigation issues emphasize the need to increase, or at least stabilize, the topsoil organic carbon content (wt%) in arable land. This on-farm study aimed at measuring the impact of agricultural practices on changes in soil organic carbon (SOC) content over 10 years. A total of 120 fields belonging to 120 farms representative of the cropping systems and soil properties in Western Switzerland (Lake Geneva region) was randomly selected. The field 0–20 cm topsoil was sampled at a 10-years interval, and the corresponding cropping practices were gathered using farmer's interviews and the mandatory records of yearly practices at field level in Swiss-farms. Only 1) organic matter inputs and 2) cover-crop intensity were significantly correlated to SOC increase while 3) the soil tillage intensity and 4) the soil saturation in carbon expressed as a SOC to clay content ratio were correlated to SOC decrease. Among others, temporary meadows were not correlated to changes in SOC content mainly due to increased tillage and decreased cover-crops between meadows. Organic farming did not correlate either with SOC changes due to the large tillage intensity applied for weed control. The observed SOC content changes ranged from –56‰ to +74‰ and were well explained by a linear regression model with additive effect of the four identified SOC change factors. The additivity of these factors means that farmers can emphasize the methods of their choice when regenerating their soils. This study advocates that strict no-till is not required at low carbon saturation level (small SOC:Clay ratio). However, as carbon saturation increases, conservation tillage and then no-till practices become necessary to further increase SOC contents. These findings are in accordance with previous studies showing that since 2015 SOC is increasing at more than +4‰ on average in the region and provide practical insights to further manage the transition of farming systems towards soil regeneration.

Keywords: soil organic carbon, soil organic matter, carbon content change, tillage, cover-crop, organic amendments, meadow, on-farm results

Abbreviations: AMG, model from Andriulo, Mary and Guerif on soil carbon dynamics (Andriulo et al., 1999); ANOVA, Analysis of Variance; ISMO, stability index of organic matter; LTE, Long Term Experiment; OM, Organic Matter; PCA, Principal Component Analysis; SEM, Standard Error of the Mean; SOC, Soil Organic Carbon; STIR, Soil Tillage Intensity Rating; STIRAC, Soil Tillage Intensity Rating calculated over annual crops' duration.

1 INTRODUCTION

According to Olson et al., 2014, carbon sequestration is “the process of transferring CO₂ from the atmosphere into the soil of a land unit, through plants, plant residues and other organic solids which are stored or retained in the unit as part of the soil organic matter (humus).” A sequestration for at least 20 years is often chosen as a criterion (IPCC, 2006). The 4-per-mille initiative (Minasny et al., 2017) has raised high hopes on the potential of this Negative Emission Technology (NET) to contribute to ecological transition by mitigating the increase in atmospheric CO₂ due to fossil energy consumption. Briefly, it suggests that increasing by a factor of 1.004 every year the soil organic carbon (SOC) stocks in the soil upper layer would significantly reduce the CO₂ concentration in the atmosphere. The feasibility of this initiative has been highly disputed (Powlson et al., 2011; Baveye et al., 2018; De Vries, 2018; Minasny et al., 2018; White et al., 2018; Chenu et al., 2019; Rumpel et al., 2020). The potential of this NET in agricultural soils, however, was underlined by two assessment reports of European Academies Science Advisory Council (EASAC, 2018, 2019). Consequently, much of the literature has been devoted to seeking methods achieving this objective (Dignac et al., 2017; Zomer et al., 2017; Chenu et al., 2019; Rumpel et al., 2020). These studies have mainly highlighted the potential of agricultural practices belonging to the pillars of Conservation Agriculture (Hobbs et al., 2008), i.e., continuous soil cover by plants and residues, limited tillage and diversification of crop rotation.

Regardless of climate issues, SOC is a major factor of topsoil fertility (Bünemann et al., 2018; King et al., 2020). In the second half of the 20th century, intensified agriculture caused a sharp decrease in topsoil SOC content (wt%) (McLauchlan, 2006), estimated at 50–70% of initial topsoil SOC content (Kucharik et al., 2001; Lal, 2004; Sanderman et al., 2017). This decrease was attributed to intense soil disturbance, shortening of the rotation lengths and export of the crop residues (West and Post, 2002; Reicosky, 2003; McLauchlan, 2006; Smith et al., 2012). Therefore, considerations including decline of soil quality and provision of ecosystem services are put forward to call for restoration of the SOC content in arable land (Swinton et al., 2007; Power, 2010; Blanco-Canqui et al., 2013), rather than focusing on carbon sequestration alone which may lead to hazardous practices for soil quality (Baveye et al., 2020). Moreover, the desirable SOC content in cropland was often related to the concept of clay complexation and saturation with organic carbon. This concept is expressed as a SOC:Clay ratio (Dexter et al., 2008; Johannes et al., 2017; Prout et al., 2020) that can be used to calculate carbon sequestration potential (Merante et al., 2017; Chen et al., 2019; Dupla et al., 2021).

Whether increasing the SOC content and SOC stock of the topsoil in cropland is an achievable objective is still highly disputed (e.g., Chambers et al., 2016; Baveye et al., 2018; White et al., 2018; Chenu et al., 2019; Paustian et al., 2019; Amelung et al., 2020; Giller et al., 2021). Highly contrasting conclusions are reported, particularly with respect to the potential of no-till practices and their influence on SOC loss (Dimassi et al., 2014;

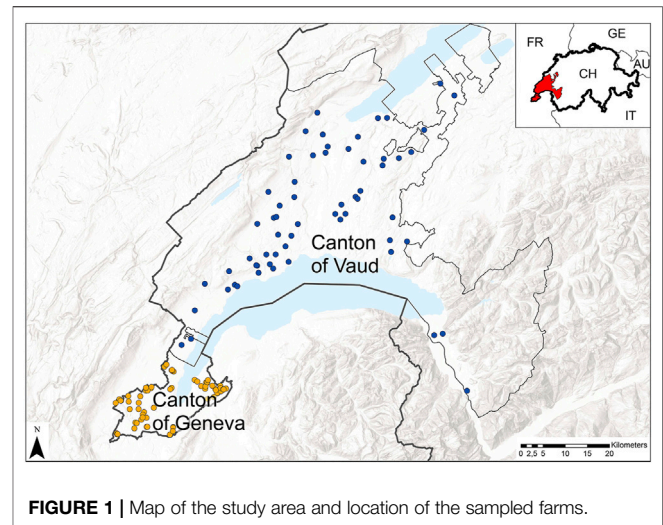


FIGURE 1 | Map of the study area and location of the sampled farms.

Powlson et al., 2014; Haddaway et al., 2017). However, most of these results were obtained on long term experiments (LTE).

A recent study performed on the Swiss long-term experiments reported negative annual change rates in SOC content of the 0–20 cm topsoil for all the LTEs regardless of the cropping system (Keel et al., 2019). Conversely, in another large scale on-farm study conducted in the Lake Geneva region, Dupla et al. (2021) showed that the SOC content of the cropland 0–20 cm topsoil was increasing on average, with annual SOC change rates ranging from less than –30‰ to more than +30‰. With a cropland mean SOC annual change rate increasing from –5‰ at the end of the 20th century to more than +5‰ at present, this study contradicted Keel et al. (2019) findings, though performed under the same climate and soil conditions. Consequently Dupla et al. (2021) concluded that LTE results cannot be extrapolated to farm fields, as already underlined by previous studies (Govaerts et al., 2009; Cook et al., 2013).

Based on the findings of Dupla et al. (2021), this study was performed in the same geographical area, namely in the Vaud and Geneva cantons—Switzerland. Here, we explored the relationships between the observed SOC content annual change rates in the 0–20 cm topsoil and the cropping practices, over the past 10 years, for 120 fields and farms representative of the soils and cropping systems of this region. Special attention was given to the practices commonly recognized as possible SOC content change factors such as cover crops and green manure, organic manure application, soil tillage intensity and temporary meadow.

2 MATERIALS AND METHODS

2.1 Study Area

This study was conducted on 120 farms from Western Switzerland (Lake Geneva region), namely Geneva and Vaud cantons, western Switzerland (**Figure 1**). The climate is oceanic (Cfb) in the plains according to Köppen-Geiger climate types (Peel et al., 2007). The dominant soil type is Cambi-Luvisol (IUSS

TABLE 1 | Distribution of soil organic carbon (SOC) (%), clay (%), SOC to clay ratio (%), SOC:Clay ratio (%) and annual SOC change rates (‰) for Geneva and Vaud croplands.

Region	Parameter	n (fields)	Min	Max	Median	Mean (SE)
Canton of Geneva	SOC (% g g ⁻¹)	1'206	0.58	2.49	1.45	1.49 (0.35)
	Clay (% g g ⁻¹)	493	11.00	39.08	23.20	23.43 (5.37)
	SOC:Clay ratio (%)	493	2.94	13.04	6.24	6.57 (1.74)
	SOC change rate (‰)	184	-28.95	+28.04	+1.74	+2.01 (11.71)
Canton of Vaud	SOC (% g g ⁻¹)	12'108	0.060	3.48	1.62	1.74 (0.57)
	Clay (% g g ⁻¹)	1'265	7.40	35.70	19.60	20.28 (5.34)
	SOC:Clay ratio (%)	1'265	3.05	13.73	7.94	8.13 (2.02)
	SOC change rate (‰)	754	-30.16	+32.60	+3.41	+3.72 (11.59)

Working Group WRB, 2014), developed on calcareous Pleistocene moraines mixed with some Tertiary molasse fragments (local parent rock). Other soil types were not considered, and only farms with annual crops in the rotation were included (livestock farms relying exclusively on permanent meadows were not considered).

To receive ecological subsidies, Swiss farmers are required to analyze a topsoil (0–20 cm) composite sample from each of their field in a certified laboratory at least every 10 years. This sampling method was assessed as an unbiased and reliable method to determine SOC annual change rates at farm scale (Deluz et al., 2020). The corresponding database contains more than 35'000 soil analyses from 1993 to present and was used by Dupla et al. (2021) to determine the regional SOC annual change rate distribution and its change with time. The corresponding parameters are summarized in **Table 1**.

2.2 Farm Selection and Data Collection

The 120 farms were randomly selected using the regional farming directory. One field per farm was randomly selected and the mandatory information recorded by farmers in their logbooks over the past 10 years was used to describe the farming practices conducted on the field. These include the different operations conducted on each field (soil preparation, fertilization, treatments, yield, cover-crops, and rotation) with the date and quantity of each product used or harvested. One-to-one in-depth interviews were conducted with the 120 farmers to validate their practices and complete them in case of missing information in the logbook. The survey included the different farming types in the region, such as organic, conventional, presence or absence of livestock.

We focused on the cropping practices potentially impacting SOC content changes, namely temporary meadow duration, cover-crop properties, organic matter application, soil tillage intensity and rotation diversity. These factors are described below and summarized in **Table 2**.

2.2.1 Cover-Crops

The numbered cover-crops only included green-manure, i.e., cover-crops whose residues are left on the field. Harvested or grazed cover-crops were considered as standard crops. The cover-crop biomass was not recorded in the past-ten years; however, we could calculate 1) the number

TABLE 2 | Main cropping practices considered in the study.

Cropping Practice	Description
Temporary meadow	Fraction of temporary meadow cover, averaged over 10 years in %
Spring crops	Number of spring crops
Cover-crop species	Mean number of species in the cover-crops
Fallow periods	Number of uncovered periods over the annual crop duration normalized to a 10-year period
Organic matter input	Mean input of humified organic matter in t.ha ⁻¹ over 10 years
Rotation species	Mean number of species in the rotation
Soil tillage intensity rating	Mean soil tillage intensity rating per year (STIR)
Soil tillage intensity rating over the annual crop duration	Mean soil tillage intensity rating per year of annual cropping (excluding periods in temporary meadow) over 10 years (STIR _{AC})

and duration of long-lasting cover-crops (between summer harvest and a spring crop seeding); 2) the number and duration of short cover-crops (between a summer harvest and an autumn-crop seeding); and 3) the number of species in the cover-crops.

However, there is an obvious relationship between the number of cover-crops and the temporary meadow duration. Therefore, to better account for the efforts of the farmer to cover the soil independently from the proportion of temporary meadow in the rotation, an uncovered soil score was created to quantify cover-cropping missed opportunities. Over the rotation, the number of fallow periods longer than 6 weeks and not covered with a cover-crop was divided by the number of annual crops and then normalized to a 10-year period. For instance, in a 6-years rotation made of 4 annual crops and 2 years of temporary meadows, a farmer who has missed 2 opportunities to use cover crops would get a score of $2 \times 10/4 = 5$ equivalent to 5 cover-cropping missed opportunities over a 10-years rotation made only of annual crops.

2.2.2 Organic Matter Application

Organic amendments were standardized as humified organic matter inputs in t.ha⁻¹ over the 10-year period. The amount of organic matter application (manure, slurry, digestate, and compost) was transformed to humified organic matter inputs depending on the organic amendment nature and form using the coefficients of specific stability index of organic matter (ISMO)

TABLE 3 | Summary of the main soil properties and cropping practices. Soil organic carbon content (SOC) (%) and clay content (%) at the beginning of the 10-year period and their ratio (SOC:Clay ratio) (%). Rate of SOC annual change (%). Share of temporary meadows in 10 years (%). Share of spring crops in 10 years (%). Mean number of species in the cover-crops. Number of fallow periods in 10 years. Cumulated organic matter amendments in humified organic matter in tons per 10 years. Number of species in the rotation. STIR: Mean Soil Tillage Intensity Rating per year over the 10-year period. STIR_{AC}: Mean Soil Tillage Intensity Rating per year over the 10-year period.

Canton	Variables	Minimum	Maximum	Median	Mean	SEM
Geneva	SOC (% g g ⁻¹)	0.81	2.97	1.51	1.52	0.06
	Clay (% g g ⁻¹)	10.85	54.50	23.15	24.65	0.96
	SOC:Clay ratio (%)	3.33	12.01	6.45	6.41	0.22
	SOC change rate (‰)	-56.28	73.73	0.00	2.29	2.47
	Temporary meadow (%)	0.00	70.00	0.00	8.00	0.02
	Spring crops (%)	0.00	60.00	20.00	23.00	0.02
	Cover-crop species	0.00	10.30	5.00	5.10	0.40
	Fallow periods	0.00	10.00	3.65	3.72	0.34
	OM input (t.ha ⁻¹ .10 years ⁻¹)	0.00	64.69	0.00	4.74	1.33
	Rotation species	3.00	7.00	5.00	5.03	0.14
	STIR	6.00	208.57	111.50	97.31	7.55
	STIR _{AC}	6.00	255.50	118.00	102.09	7.88
	Vaud	SOC (% g g ⁻¹)	0.87	3.19	1.57	1.68
Clay (% g g ⁻¹)		8.90	41.00	18.20	20.01	0.73
SOC:Clay ratio (%)		4.38	16.34	8.12	8.67	0.34
SOC change rate (‰)		-39.34	66.79	8.48	8.04	2.56
Temporary meadow (%)		0.00	63.00	12.00	19.00	0.03
Spring crops (%)		0.00	90.00	25.00	30.00	0.03
Cover-crop species		0.00	10.43	3.00	3.12	0.30
Fallow periods		0.00	7.86	2.93	2.65	0.26
OM input (t.ha ⁻¹ .10 years ⁻¹)		0.00	69.71	16.64	17.87	1.75
Rotation species		3.00	9.00	5.00	4.67	0.15
STIR		6.77	195.70	117.01	107.77	5.80
STIR _{AC}		7.12	245.28	121.95	118.10	6.62
Vaud and Geneva		SOC (% g g ⁻¹)	0.81	3.19	1.51	1.60
	Clay (% g g ⁻¹)	8.90	54.50	21.05	22.33	0.64
	SOC:Clay ratio (%)	3.33	16.34	7.20	7.54	0.23
	SOC change rate (‰)	-56.28	73.73	0.00	5.16	1.79
	Temporary meadow (%)	0.00	70.00	0.00	13.00	0.02
	Spring crops (%)	0.00	90.00	25.00	26.00	0.02
	Cover-crop species	0.00	10.43	3.55	4.11	0.26
	Fallow periods	0.00	10.00	3.00	3.19	0.22
	OM input (t.ha ⁻¹ .10 years ⁻¹)	0.00	69.71	6.59	11.31	1.25
	Rotation species	3.00	9.00	5.00	4.85	0.10
	STIR	6.00	208.57	114.50	102.54	4.76
	STIR _{AC}	6.00	255.50	121.43	110.10	5.18

(Bouthier et al., 2014) used in the AMG model (Andriulo et al., 1999; Levasseur et al., 2020).

2.2.3 Soil Tillage Intensity Rating

The index of Soil Tillage Intensity Rating (STIR) (USDA, 2003) was used to estimate overall soil disturbance based on specific standardized scores attached to soil management practices. A single tillage operation to 23 cm depth gives for instance a score of 74, while direct seeding would give a score of 4. For each investigated field, all soil management practices over the last 10 years were considered to calculate STIR values. The cumulated values were then divided by ten to obtain the variable subsequently referred to as STIR.

Like cover-crops, the average tillage intensity over 10 years is highly influenced by the share of temporary meadow. To take into account the soil tillage intensity applied on annual crops regardless of temporary meadow duration in the rotation, a second index

denoted STIR_{AC} was also calculated over the annual crops duration in the rotation and then normalized to 10 years.

2.2.4 Temporary Meadow

Temporary meadow duration was expressed as percentage over the 10-year period.

2.3 Soil Sampling and Analysis

The selected fields were sampled at the beginning and the end of the 10-years interval by collecting 15 to 20 aliquots along the field diagonals at 0–20 cm depth to obtain a composite sample (Deluz et al., 2020). SOC and clay contents (wt%) were analyzed using Walkley-Black (Nelson and Sommers, 1983) and pipette methods (Jennings et al., 1922; Robinson, 1922), respectively.

This allowed the SOC:Clay ratio of the field to be calculated. The 10-years mean SOC annual change rate (‰) of each field

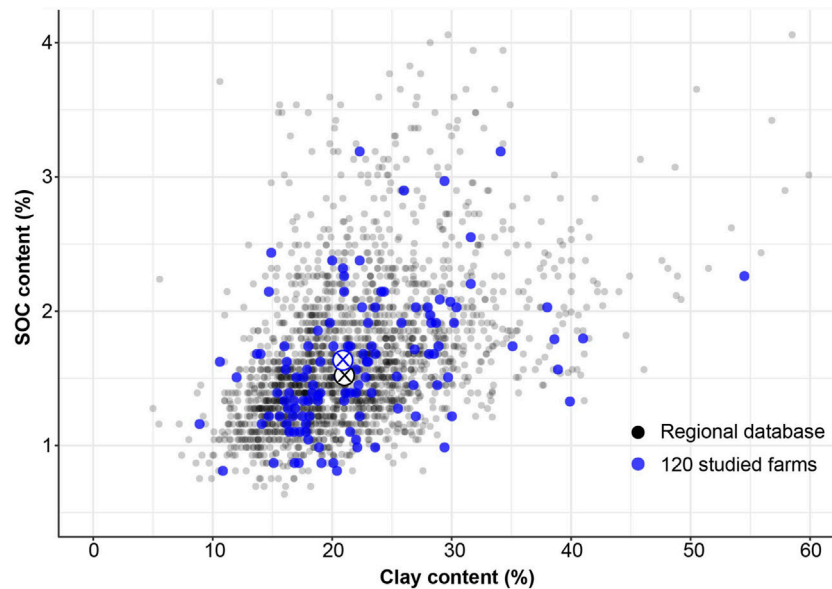


FIGURE 2 | SOC vs. clay contents (circles) and respective centroids (circled X) of soil samples from the regional Geneva and Vaud database (grey) and from sampled fields of the 120 surveyed farms (blue).

being the equivalent of the common ratio in a geometric sequence, it was calculated using Eq. 1 (see **Supplementary Material** for additional computational explanations).

$$\text{SOC annual change rate (\%)} = 1000 \times \left(\left(\frac{\text{SOC}_2}{\text{SOC}_1} \right)^{\frac{1}{n}} - 1 \right) \quad (1)$$

with SOC_1 and SOC_2 being the SOC contents of the soil at the beginning (SOC_1) and end (SOC_2) of the period, and n the number of years between the two analyses ($n = 10$).

2.4 Statistical Analysis and Modelling

All statistical analyses and modelling were performed with R (v 4.0.3, R Development Core Team 2020). Variables of interest included the SOC annual change rate, the clay content, the initial SOC content, the initial SOC:Clay ratio and eight cropping practices averaged over the 10 years (**Table 2**). All variables were quantitative. For each cropping practice, we also created a class variable which was subsequently used in an analysis of covariance (see below).

For each quantitative variable, the mean and median were calculated to represent the central tendency and the minimum, maximum and standard error of the mean (SEM) to represent dispersion. Linear models (simple and multiple regressions, analyses of variance and analyses of covariance—see details below) were then used to investigate relationships between the SOC annual change rate, soil properties, cropping practices and cantons. The α level for model and effect significance was set at 0.05 unless stated otherwise. Approximate normality and homogeneous variance of model residuals were assessed on residual plots.

A one-way analysis of variance (ANOVA) was conducted to test for differences in the SOC annual change rate, soil properties

and cropping practices between the two cantons. We investigated bivariate linear relationships between quantitative variables by calculating Pearson's correlation coefficients (see **Supplementary Table S1**). Significant correlations between the SOC annual change rate and other variables were further described with simple linear regressions.

A multiple regression analysis was subsequently conducted to account for the cumulative effect of soil properties and cropping practices on the SOC annual change rate (McCullagh and Nelder, 1989). The dependent variable was the SOC annual change rate, and predictors were selected among variables representing cropping practices and the initial SOC:Clay ratio. To maximize validity, reliability and parsimony (Chatfield, 1995), the regression analysis was not performed on the maximum model (the model containing all the potential predictors). Unimportant variables were first discarded during a model selection process consisting of a stepwise selection using an α level of 0.15 for both variable entry and variable removal. A permissive alpha level of 0.15 was used to make sure that any predictor potentially influencing the response variable remained included in the model. The multiple regression analysis was then conducted on the resulting model; the significance of predictors was from here on assessed using the regular alpha level of 0.05. To reduce model instability arising from variable collinearity, we excluded moderately to highly correlated predictors, defined here as variables having absolute correlation coefficients greater than 0.3. Multi-collinearity was low, and partial least square or ridge regression approaches did not yield any improvement.

To check for the robustness of the multiple regression result, we repeated the analysis using a covariance model, with the SOC annual change rate as dependent variable, the SOC:Clay ratio as a covariate, and cropping practices as class effects. Models using class variables as predictors are generally more robust to potential

TABLE 4 | Pearson correlation coefficients and *p*-value of the significant correlations between rates of SOC annual change, cropping practices, and soil properties. SOC refers to the soil organic carbon content at the beginning of the 10-year period.

Variable	Variable	Pearson Correlation	<i>p</i> -value
SOC change rate (‰)	Number of cover-crop species	0.18	0.050
SOC change rate (‰)	Fallow periods	-0.30	0.001
SOC change rate (‰)	OM input (t.ha ⁻¹)	0.31	0.001
SOC change rate (‰)	STIR _{AC}	-0.27	0.002
SOC change rate (‰)	STIR	-0.30	0.001
SOC change rate (‰)	SOC:Clay (%)	-0.27	0.003
SOC:Clay (%)	Temporary meadow share (%)	0.22	0.018
SOC:Clay (%)	Number of cover-crop species	-0.27	0.003
SOC:Clay (%)	OM input (t.ha ⁻¹)	0.20	0.026
Temporary meadow share (%)	Spring crops share (%)	-0.26	0.004
Temporary meadow share (%)	Number of cover-crop species	-0.28	0.002
Temporary meadow share (%)	STIR _{AC}	0.26	0.004
Temporary meadow share (%)	STIR	-0.24	0.009
Cover-crop species	STIR _{AC}	-0.44	<0.001
Cover-crop species	STIR	-0.32	<0.001
Cover-crop species	Number of species in rotation	0.20	0.030
Fallow periods	STIR _{AC}	0.23	0.012
Fallow periods	STIR	0.23	0.011
Fallow periods	Spring crops share (%)	-0.48	<0.001
Fallow periods	Number of species in rotation	-0.19	0.041
STIR	STIR _{AC}	0.85	<0.001
STIR	Spring crops share (%)	0.25	0.006

collinearity effect. Results were similar to what was obtained using multiple regression approaches and are presented in the Supplementary Material (see **Supplementary Table S2**). Due to the relatively high number of predictors, interaction effects could not robustly be assessed.

We used a Principal Component Analysis (PCA) (Wold et al., 1987) based on the correlation matrix to illustrate the relationship between the significant agricultural practices related to SOC annual change rates.

3 RESULTS

3.1 Properties of the Sampled Fields and Surveyed Cropping Practices

The selected farms have a mean cultivated surface area of 50 ha, which is slightly above the mean size observed in the region (36 ha) and 15% of the farms were under Swiss organic farming label, which is slightly above the regional mean (11%). 48% of the farms had no livestock, and the average livestock units in the other farms was 10 which lies in the mean regional range (5.8–20.5).

The properties of the studied fields and the related cropping practices averaged on the 10-year period are reported in **Table 3**. Due to differences in agriculture management history, the cropping systems in the two cantons showed some differences. Livestock was more developed in Vaud farms than in Geneva farms. Geneva canton subsidizes cover crops of short fallow periods (e.g., from barley to colza) contrary to Vaud, and the

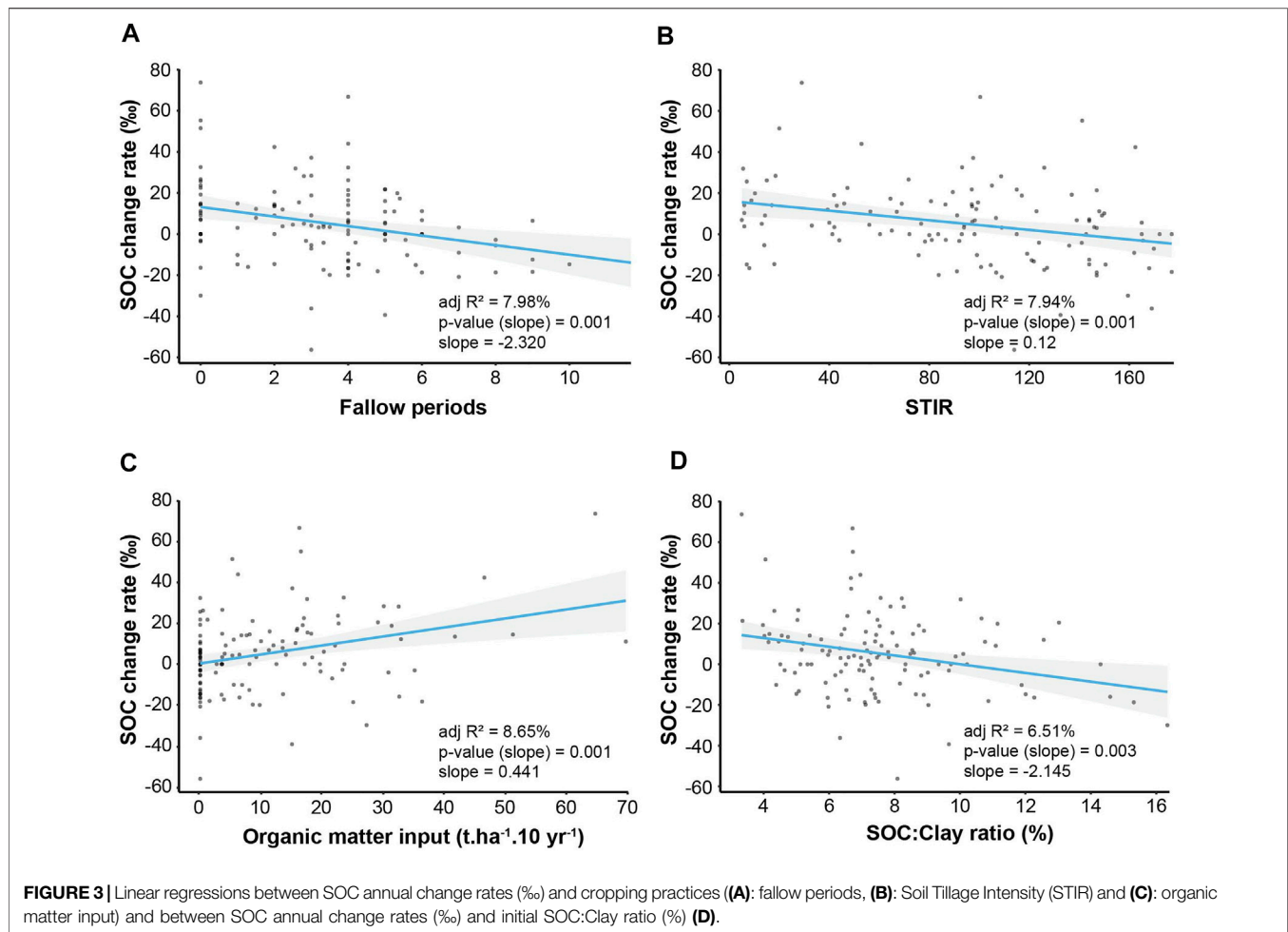
rotations show little variation in spring crop frequency in Geneva compared to Vaud, which explains the differences in the corresponding cover-crop properties. However, the canton effect was not significant on the SOC annual change rate and its relationships with other variables.

The distributions of initial SOC and clay contents are presented in **Figure 2**, together with the values observed in the regional data base used in Dupla et al. (2021). As can be seen from their centroid and their distribution, the sampled fields from the 120 farms are representative of the regional SOC and clay contents, and SOC:Clay ratio distribution.

The observed rates of SOC annual change show a median value of 0 and ranged from -56‰ to +74‰. These change rates display a similar pattern to the rates found at the regional scale by Dupla et al. (2021) (**Table 1** and **Table 3**) despite a higher dispersion compared with the minimum and maximum rates (-30.12 and +32.47‰, respectively) in both cantons. According to ANOVA, the soils from Vaud had significantly less clay and a higher SOC:Clay ratio than in Geneva, but the SOC change rate was not significantly different between cantons, which is similar to the observations of the regional database study.

3.2 Pearson Correlations and Linear Regressions

Significant Pearson correlation coefficients between the observed rates of SOC annual change, the soil analyses, and the investigated cropping practices are presented in **Table 4**.



Among the cropping practices, only the cover-crop related properties, STIR, and OM inputs showed significant correlation with the SOC annual change rate. Among the cover-crop properties, the number of fallow periods showed the largest and most significant correlation to SOC change rate (-0.3 , p -value = 0.0009) and was, therefore, used in the multivariate analysis. The number of species in the cover-crops showed a positive effect on the SOC change rate (0.18 , p -value = 0.0496). The STIR (-0.3 , p -value = 0.001) and the STIR_{AC} (-0.27 , p -value = 0.002) were negatively correlated to the SOC change rate. Due to its stronger significance, the STIR rather than the STIR_{AC} was used in the multivariate analysis. The organic matter input was positively correlated to SOC change rates (0.26 , p -value = 0.0042). Interestingly, neither the proportion of temporary meadow in the rotation nor the crop rotation diversity had a significant effect on the SOC annual change rate. The linear regressions between SOC annual change rates, SOC:Clay ratios and cropping practices are presented in **Figure 3**.

Among the soil properties, the SOC content and SOC:Clay ratio at the beginning of the 10-year period showed a negative correlation with the SOC annual change rate, namely -0.26 (p -value = 0.004) and -0.27 (p -value = 0.003), respectively. The correlations with the annual change rates and the other SOC

change factors were more significant when using SOC:Clay ratio rather than with SOC alone (see **Supplementary Table S1**).

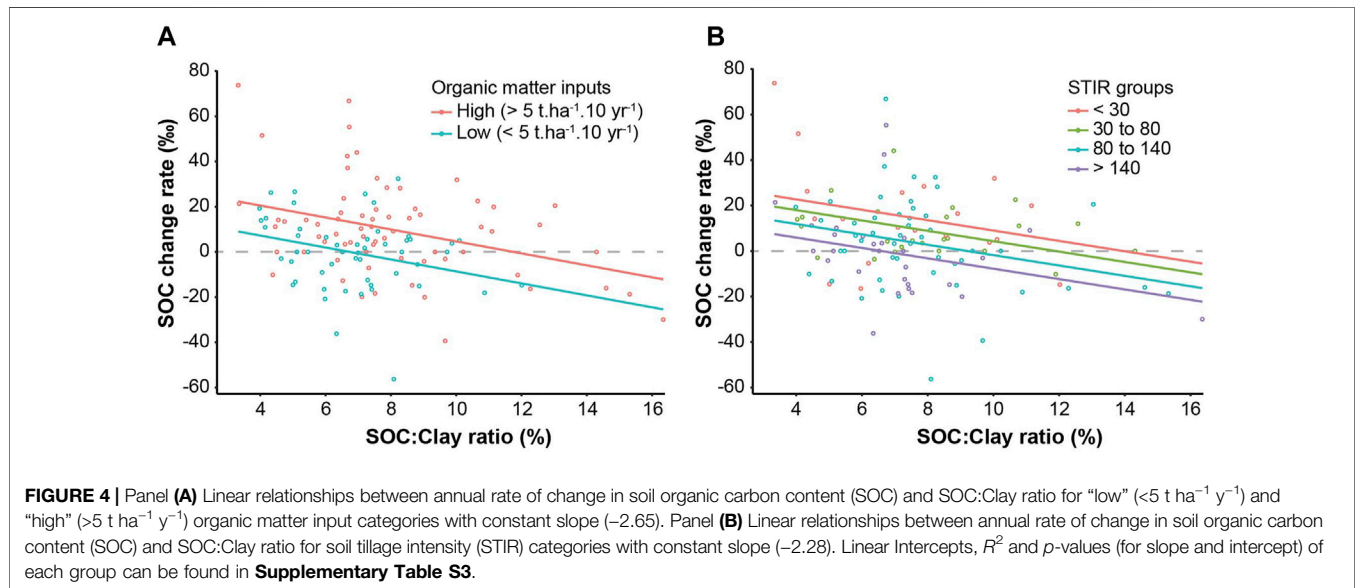
Some practices were significantly cross correlated. The STIR showed negative correlation to the cover-crops related indexes, such as number of species (-0.32 , p -value < 0.001) and fallow periods (0.23 , p -value = 0.01), as well as with temporary meadow duration (-0.24 , p -value = 0.009) and spring crops share (0.25 , p -value = 0.006). STIR_{AC} showed similar correlations than STIR to all practices except spring crops (no correlation). Moreover, it showed a positive correlation to temporary meadow share (0.26 , p -value = 0.004), contrary to STIR. Organic matter input was positively correlated to temporary meadow duration (0.21 , p -value = 0.0236), and negatively correlated to the number of species in the cover-crops (-0.21 , p -value = 0.0222) and fallow periods (-0.25 , p -value = 0.006). This latter was negatively correlated to temporary meadow duration (-0.3 , p -value = 0.0008).

3.3 Multivariate Analysis

According to stepwise regression, the independent variables that showed significant contribution to SOC change rates were the SOC:Clay ratio at the beginning of the period, fallow periods,

TABLE 5 | General linear model of SOC annual change rates as a function of farming practices and soil properties.

Variable	Parameter Estimate	Standard Error	Pr > t	Model Adj. R^2
Intercept	37.03	5.83	<0.001	—
Organic matter input	0.53	0.11	<0.001	0.086
SOC:Clay ratio	-2.95	0.61	<0.001	0.196
STIR	-0.12	0.03	<0.001	0.311
Fallow periods	-1.26	0.62	0.043	0.329



STIR, and OM inputs. Since the covariance model with practices as class effects provided similar results to the linear regression model, we only present results from the latter (see **Supplementary Table S2** for covariance results).

The results of the stepwise regression are presented in **Table 5**. All variables left in the model, namely the initial SOC:Clay ratio, fallow periods, STIR, and OM inputs, are significant at the 0.05 level. No other variable met this significance level for entry into the model. Introducing organic farming yielded no significant effect as well.

According to stepwise regression analysis, OM input had a positive influence on SOC change rates while the initial SOC:Clay ratio, the proportion of fallow periods, and the tillage intensity had a negative influence. Other predictors such as meadow and spring crop share were not significant. The ranking of the relative effects, based on the partial R^2 , was not performed because of small effects and some collinearity among predictors. The corresponding model was additive and accounted for 33% variance of the annual SOC change rate.

The combined effect of the practices was illustrated by representing the linear relationships between SOC change rates and SOC:Clay ratios for different categories of OM input (**Figure 4A**) and STIR (**Figure 4B**). In both cases, the interaction between the categories and the slopes were not significant. Therefore, we kept a constant slope for the categories. **Figure 4A** shows that the larger the SOC:Clay

ratio, the smaller the annual SOC change rate for a given OM input, with neutral SOC change rates on average at a SOC:Clay ratios of 7 and 12% for OM input categories of $< 5 \text{ t ha}^{-1} \text{ yr}^{-1}$ and $> 5 \text{ t ha}^{-1} \text{ yr}^{-1}$, respectively.

Figure 4B illustrates the role of the initial clay saturation status (SOC:Clay ratio) with respect to SOC increase and tillage intensity. Positive SOC change rates with large tillage intensities are mostly observed at small SOC:Clay ratios and more generally, the higher the SOC:Clay ratio, the lower the STIR needs to be to allow for a SOC increase. In other words, no-till becomes increasingly necessary at large SOC content, but is not required to increase SOC content at low clay saturation level.

4 DISCUSSION

4.1 Significant Predictors Influencing Soil Organic Carbon Annual Change Rates

The correlations between the cropping practices depict different cropping systems that can be summarized as follows. The proportion of temporary meadow is largely varying between farms and between cantons. The larger this proportion, the higher the organic matter input, the initial SOC:Clay ratio, the $STIR_{AC}$, the proportion of fallow periods corresponding to cover-cropping missed opportunities in the rotation, the spring crops share, and the lower the cover-crop

diversity. Moreover, regardless of temporary meadow duration, STIR was highly variable, and the use of cover-crops (duration and diversity) was inversely proportional to the mechanical intensity (see **Supplementary Figure S1**). This means that 1) farmers having livestock and temporary meadow tend to apply high mechanical intensity and neglect cover-crops while applying more OM inputs; that 2) mechanical intensity in general jeopardizes cover-crop intensification; and that 3) farmers having no temporary meadows tend to reduce soil tillage intensity and to grow cover-crops to regenerate effective soil quality losses due to decades of intensive agriculture.

Data analysis shows that the only factors influencing significantly rates of SOC annual change are the cover-crops (intensity and diversity, positive effect), organic matter inputs (positive effect), and the mechanical intensity applied to the annual crops (negative effect). They represent, therefore, the pillars of SOC increase. Organic farming, temporary meadow duration as well as rotation diversity showed no significant effect, though often referred-to in the literature as soil regenerating and/or carbon sequestration factors (Fließbach et al., 2007; Senapati et al., 2014; Autret et al., 2016; Blanco-Canqui et al., 2017; Chenu et al., 2019; Colombi et al., 2019). Rotation diversity did not vary on a large range in this survey (**Table 3**). Moreover, longer rotations corresponded to contrasting strategies. In some cases, it corresponded to the addition of a “cash-crop,” namely potatoes or sugar-beet, while the longer rotation was also negatively correlated to fallow periods, thus corresponding to an increased use of the cover-crops and decreased tillage intensity.

Organic matter application and cover-crops intensity and diversity are highlighted in many studies as factors of SOC increase (Maltas et al., 2013; O’Connell et al., 2015; Ruis and Blanco-Canqui, 2017; Büchi et al., 2018; Wendling et al., 2019). Their significant effect is particularly remarkable in this survey because the cover-crop biomass was not available, though it is assumed to be a key factor (Blanco-Canqui et al., 2015; Poehlau and Don, 2015) and should be even more strongly correlated to SOC change rates than our available information. However, the decreasing number of fallow periods and the number of species in the cover-crops can be considered as indicators of farmers motivation, thus increasing the likelihood of higher biomass of cover-crops. This is a common observation made by the authors and the advising services in the region (Wendling et al., 2017).

4.2 Impact of Temporary Meadows and Organic Farming

The non-significant effect of the proportion of temporary meadow on SOC change rates (see **Supplementary Figure S2**), despite its large range (from 0 to 70% of the past 10-years rotations in this survey, **Table 3**), is particularly surprising with respect to the common acknowledgment that temporary meadow may be a guarantee of sustainable soil management in agriculture. However, temporary meadow duration was positively correlated to factors associated with SOC decrease (namely the STIR_{AC} applied on the annual crops in the rotation,

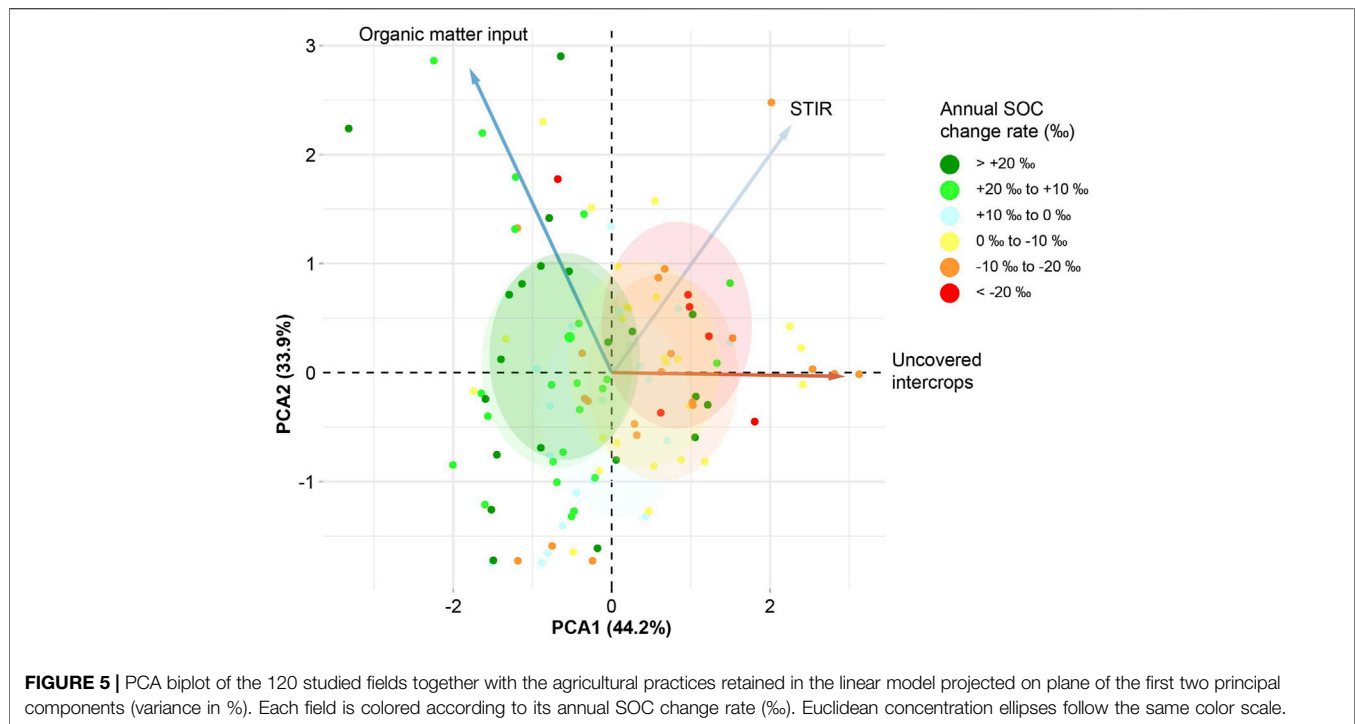
the number of fallow periods, and the SOC:Clay ratio), whereas it was negatively correlated to the number of species in the cover-crops which is considered as a key factor of SOC increase (e.g., Ranaldo et al., 2020). Moreover, there was no correlation between temporary meadow and OM inputs, which might be due to increased liquid manure and digestate application with increasing temporary meadow share, which is growingly observed. Temporary meadows, therefore, are not conducive to increasing the SOC content, especially when SOC:Clay ratio was already high. From this point of view 1) the larger SOC:Clay ratio observed with temporary meadows appears to be inherited from the past and is decreasing and 2) this should be mitigated by increasing OM inputs and/or decreasing tillage intensity and increasing cover-crop intensity on the annual crops.

Organic farming had no significant effect on SOC change rates as a predictor (see **Supplementary Figure S3**). It performed according to the intensity of application of the SOC increase factors. Organic farming is often associated with livestock and manure application but also to a high STIR for weed control, which is the case in this data set (see **Supplementary Figure S4**).

4.3 Soil Tillage is the Only Significant Factor Decreasing Soil Organic Carbon Annual Change Rates

The only practice accounting for SOC content decrease was the mechanical intensity. This may appear contradictory to some findings, such as Dimassi et al. (2014) or Powlson et al. (2014), who reported limited or no effect of tillage compared with no-till practices. However, these results were obtained in LTEs. They were observed under constant treatment over a long time, with site-specific SOC:Clay ratio, cropping practices and climate conditions, and with tillage as unique difference between the treatments. Such research is designed to quantify the potential SOC mineralization by tillage. Conversely, our observations cover a large range of soil conditions and practices interacting in the cropping systems. In particular, **Table 4** shows that the Pearson correlation coefficient between STIR and fallow periods was positive (0.31, p -value = 0.0006). This can be related to a well-known observation that working the soil after a summer harvest not only delays the seeding of the cover-crop, but also dries out the soil down to the tillage limit, thus retarding seed emergence until significant rainfall events, usually occurring during fall in this region (Büchi et al., 2018). As a result, many farmers choose not to seed cover-crops in such conditions, or the seeded cover-crop shows a late development and reaches small biomass. Therefore, although the present on-farm results cannot adjudicate on the precise impact of soil tillage on SOC mineralization, they show that in a systemic perspective, soil tillage compromises the main SOC increase factor, namely cover-crops.

Additionally, threshold values of mechanical intensity can be derived from **Figure 4B**. Fields with conventional tillage (STIR > 140), conservation tillage (80 > STIR > 140) or no-till (STIR < 30) display positive SOC change rates up to SOC:Clay ratios of 7, 10 and 14% on average, respectively. These latter SOC:Clay ratios



coincide with the soil structure vulnerability thresholds for poor, acceptable and optimal soil structures, respectively, (Johannes et al., 2017; Prout et al., 2020), thus confirming the relevance of these thresholds for SOC management.

4.4 Multivariate Analysis and Insights for Soil Organic Carbon Content Management

Stepwise regression analysis provides additional information to the Pearson correlations. The model accounts for 33% of the variance of the SOC annual change rate, which may be considered small. However, there are many reasons for this limited R^2 , because 1) the independent variables were collected from farmers and averaged over 10 years, which does not mean that they were constant during this period since cropping systems are continuously changing; 2) the climate conditions were different each year, with alternating wet and dry conditions in spring and autumn, thus sharply modifying the harvest dates and the cover-crops development conditions; and 3) the cover-crop biomass was not known though most likely representing the key information, which could be assessed by simulating the cover-crop biomass with the collected information and meteorological data. **Figure 5** presents the distribution of the fields with respect to the two first principal components of the retained three agricultural practices accounting for SOC content change. The more intensely one practice was used, the more towards the practice's arrowhead each field would be positioned. Conversely, if one practice was avoided (e.g., no-till for the STIR parameter) then the field would be located at the opposite end of the practice's arrow in the PCA biplot. The SOC change rate categories display a gradual shift of concentration ellipses

towards higher STIR, organic matter inputs and fallow period values as SOC change rates decrease. This gradual distribution casts light on the beneficial impact of low tillage intensity, organic amendments and intense cover-cropping on SOC content change.

The absence of clear statistical interactions implies that the roles of the different factors are additive. If so, farmers may select which SOC increase factors to emphasize when adapting their system. However, the higher the clay saturation by SOC, the more intense the use of the different factors should be, as illustrated for instance with tillage intensity in **Figure 4B**. Therefore, farmers could select the intensity to apply on the different SOC increase factors depending 1) on their cropping system, 2) whether they are in a regeneration strategy or not, and 3) their SOC:Clay ratio.

The observed SOC annual change rates are consistent with the regional study of Dupla et al. (2021). Contrary to findings in Swiss LTEs (Keel et al., 2019) many Swiss farms do increase their SOC content at a larger rate than 4% and the factors seem clearly identified. However, large negative SOC change rates are also observed, which could be corrected in the future by applying the corresponding changes in the cropping practices.

4.5 Implications for Soil Research

Together with the study of Dupla et al. (2021), these results may seem very contradictory with previous findings on SOC dynamics in arable land. The impact of tillage on SOC dynamics is considered negligible by Powlson et al. (2014) or Dimassi et al. (2014) while its strong negative effect appears in this on-farm study. In Swiss LTEs, all cropping practices, including conservation agriculture, induced a decrease in SOC according

to the study by Keel et al. (2019) while high rates of SOC content increase are found on-farm. Experimental conditions in LTEs can deviate significantly from on-farm conditions, as illustrated in this study. On-farm practices are the result of systemic decisions considering different factors that co-evolve from year to year, whereas in LTEs we aim to quantify mechanistic processes by comparing the effects of single factors over the long term from a unique research perspective. For example, our results show that the higher the SOC:Clay ratio, the more detrimental the mechanical intensity can be to the SOC content, whereas in a field experiment dealing with this issue, only a narrow range of SOC:Clay ratios can be considered, thus excluding the observation of this effect. Furthermore, we have highlighted the negative interaction between tillage and cover crops, which is the result of systemic constraints and farmers' choices, another effect that will not be revealed in the LTE.

These observations call for a thorough reflection when selecting research strategies, with a clear distinction between objectives. Experimentation under controlled conditions is of paramount importance to decipher mechanisms and quantify processes. In addition, field trials can provide useful demonstrations and stimulate farmer innovation. However, the transfer of these results to the farm may not be straightforward and may even lead to misinterpretation. On-farm soil quality management clearly requires systemic research, especially for key issues such as carbon sequestration and the preservation of soil functions.

5 CONCLUSION

In 120 farms representative of Western Switzerland (Lake Geneva region) agricultural sector, the most significant factors for SOC content increase or decrease corresponded to the mechanical intensity applied on annual crops (negative effect), the organic matter inputs (positive effect), and the frequency and diversity of non-harvested cover-crops (positive effect). The temporary meadow duration had no effect on the SOC content change, due to adverse practices on the annual crops of the corresponding rotations, namely larger mechanical intensity and lower cover crop frequency with increasing meadow duration. Moreover, organic matter application did not increase with temporary meadow. Therefore, the larger SOC to clay ratios observed with temporary meadow were interpreted as inherited from the past. In such a case, temporary meadows do not guarantee sustainable soil quality management.

The factors for SOC increase or decrease were additive. Clay saturation by SOC decreased the positive effects of organic matter

inputs and cover-crops and increased the negative effects of tillage intensity. The cover-crop intensity and diversity were negatively correlated to tillage intensity, which may explain the significant negative effect of tillage intensity contrary to what was reported in some field experiments. This is consistent with a common on-farm observation that tilling the soil before seeding a cover-crop jeopardizes the chances to yield high biomass cover-crops, thus discouraging many farmers to seed expensive multi-species cover-crops especially during summer short fallow periods.

The observed SOC increases are consistent with the regional study of Dupla et al. (2021). In contrast with the results obtained in the Swiss LTEs (Keel et al., 2019), Swiss farms can increase their SOC content at a rate greater than 4%, although large negative change rates can also be found, which can be corrected in the future by applying changes in cropping practices. These results define a roadmap for SOC-increasing cropping systems in the region. The roadmap is based on progressive changes in the intensity of the different SOC content levers, depending on the current SOC:Clay ratio of the fields.

AUTHOR CONTRIBUTIONS

XD, TL and KG collected the data under the supervision of PB. SG performed the analytic calculations and statistical modelling. XD and PB wrote the manuscript with support from SG, EV and RC. All authors provided critical feedback and helped shape the content of this study.

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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.2022.834055/full#supplementary-material>

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