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Soil carbon content and its stratification at the medium-term (5 and 8 years) in a semi-arid vineyard with cover crops

Contenido en carbono del suelo y su estratificación a medio plazo (5 a 8 años) en suelos de viñedo con cubierta vegetal bajo clima semiárido
Conteúdo e variação do carbono no médio prazo (5 a 8 anos) em solos de vinha com cobertura vegetal em condições de clima semiárido

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ABSTRACT

There is little information available on the evolution and stratification of soil C content (SCC) at the medium- to long-term in semiarid vineyards with cover crops. The objective was to determine SCC at different depths in the medium term (5 and 8 years) in a semiarid vineyard with different cover crops. The field experiment was conducted on Typic Haploxerept soil with a loam texture, pH 8.2, situated in a vineyard (cv. Tempranillo) located in the La Rioja region (northeast Spain) on Miocene sandstones, siltstones, clays and marlstones. Two different soil managements were evaluated: conventional tillage (CT) and continuous cover crop of resident vegetation (RV). Soil samples were collected from four soil layers (at depths of 0-2.5, 2.5-5, 5-15, and 15-25 cm) in June 2009 and June 2012, 5 and 8 years respectively after cover crop establishment. The SCC was determined and the SCC variation with respect to tillage treatment was determined considering the percentage of soil < 2 mm and soil bulk density. The results showed that the greatest increase in SCC occurred at 0-2.5 cm soil depth, increasing less with depth. The SCC annual increment in the whole soil sampled (0-25 cm) was 2.78 Mg C ha^{-1} $year^{-1}$ after 5 years and decreased to 1.98 Mg C ha^{-1} $year^{-1}$ after 8 years of cover crop establishment. The lower SCC annual increase was not due to the maximum increase being reached in the whole of the sampled soil (0-25 cm). From 2009 to 2012, the SCC did not increase at the soil surface (0-2.5 cm), but did so in the subsurface zone (2.5-5 cm), although with an annual increment lower than that found at soil surface (0-2.5 cm). In conclusion, the steady state in SCC would not have been reached in the medium term (8 years) under cover crop, since there is still a increment of SCC in the subsurface layers.

RESUMEN

Existe escasa información sobre la evolución del contenido de C del suelo y su estratificación a medio y largo plazo en suelos de viñedo con cubierta vegetal bajo clima semiárido. El objetivo del estudio fue determinar las tasas de incremento de C a diferentes profundidades en el medio plazo (5 y 8 años) en viñedos semiáridos con cubiertas vegetales. El experimento de campo se realizó con un viñedo (cv. Tempranillo) en un suelo Typic Haploxerept con pH 8,2 y textura franca, sobre areniscas, limolitas, arcillas y margas miocenas, situado en la región de La Rioja (noreste de España). Se evaluaron dos manejos de suelos diferentes, laboreo convencional (CT) y cubierta vegetal continua de vegetación espontanea (RV). Se tomaron muestras de suelo a la profundidades de 0-2,5, 2,5-5, 5-15 y 15-25 cm, en junio de 2009 y junio de 2012, 5 y 8 años, respectivamente, después del establecimiento

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de la cubierta vegetal. Se determinó el contenido de C orgánico (CO) del suelo y la variación de CO respecto al tratamiento de laboreo convencional, considerando el porcentaje de suelo < 2 mm y la densidad aparente del suelo. Los resultados mostraron que existía más incremento del contenido de C a 0-2,5 cm de profundidad y este aumento del contenido C disminuyó al incrementarse la profundidad. La tasa anual de incremento del contenido C en todo el suelo muestreado (0-25 cm) fue de 2,78 Mg C ha^{-1} año^{-1} después de 5 años y disminuyó a 1,98 Mg C ha^{-1} año^{-1} después de 8 años del establecimeinto de la cubierta. La disminución en la tasa anual de incremento del contenido de C no se debió al hecho de que en todo el suelo muestreado (0-25 cm) se hubiera alcanzado el máximo incremento del cotenido de C. De 2009 a 2012 el contenido de C en la superficie del suelo (0-2,5 cm) no aumentó pero sí en la zona subsuperficial (2,5-5 cm), aunque con una tasa de acumulación de C menor que la encontrada en la superficie del suelo (0-2,5 cm). En conclusión, en el medio plazo (8 años) con la cubierta vegetal no se habría alcanzado el estado estable en el contenido de C, ya que todavía hay un aumento de C en las capas subsuperficiales.

RESUMO

Há pouca informação disponível acerca da evolução do teor de C e da sua variação (SCC) a médio e longo prazo em solos de vinha com cobertura vegetal em condições de clima semiárido. O objetivo deste estudo foi determinar a SCC em diferentes profundidades no médio prazo (5 e 8 anos) em vinhas com coberturas vegetais diferentes e em condições semiáridas. O ensaio de campo foi conduzido numa vinha (cv. Tempranillo) localizada na região de La Rioja (nordeste de Espanha) num solo Typic Haploxerept com textura franca, pH 8,2 e desenvolvido sobre arenitos, siltitos, argilas e margas datados do Miocénico. Foram avaliadas duas práticas culturais diferentes do solo: preparação convencional (CT) e cobertura vegetal contínua de vegetação espontânea (VR). As amostras de solo foram colhidas às profundidades de 0-2,5, 2,5-5, 5-15 e 15-25 cm, em junho de 2009 e junho de 2012, 5 e 8 anos, respectivamente, após o estabelecimento da cobertura vegetal. Determinou-se o teor de C orgânico (CO) do solo e a sua variação (SCC) em relação ao tratamento convencional, considerando-se a percentagem de solo < 2 mm e a densidade aparente do solo. Os resultados mostraram que o maior aumento no conteúdo de C ocorreu à profundidade de 0-2,5 cm e que esse aumento foi menor com o aumento da profundidade. O aumento do teor de C em todo o solo amostrado (0-25 cm) foi de 2,78 Mg C ha^{-1} ano^{-1} após 5 anos e diminuiu para 1,98 Mg C ha^{-1} ano^{-1} após 8 anos do estabelecimento da cobertura vegetal. A diminuição na taxa anual de aumento do conteúdo de C não se deveu ao fato de em todo o solo amostrado (0-25 cm) se ter atingido o aumento máximo do conteúdo em C. De 2009 a 2012, o teor de C na superfície do solo (0-2,5 cm) não aumentou mas este aumento ocorreu na zona subsuperficial (2,5-5 cm), embora com um incremento anual mais baixo do que o observado na superfície do solo (0-2,5 cm). Em conclusão, a médio prazo (8 anos) com cobertura vegetal não seria alcançado o estado estacionário no teor de C, porque há ainda um aumento do teor em C nas camadas subsuperficiais.

KEY WORDS
C steady state, conventional tillage, conservation agriculture.

PALABRAS CLAVE
Carbono en estado estabilizado, laboreo convencional, agricultura de conservación.

PALAVRAS-CHAVE
Carbono em estado estabilizado, prática cultural convencional, agricultura de conservação.

1. Introduction

Increasing the soil C content (SCC) with conservation agriculture techniques has attracted great interest in its ability to improve soil quality, because soil C sequestration can attenuate the negative effects of increasing CO_2 concentration on atmosphere (Lal 2004).

Spain is the country with the largest vineyard area worldwide, with 1,032,000 ha, and in La Rioja winegrowing area (NE Spain) where the field experiment was carried out, there are 60,000 ha of vineyard soils. Its vineyards are mainly under Mediterranean semiarid conditions, and traditional tillage is the common management method used to prevent weeds that have to compete with vines for soil water. Soil tillage buries residues, disrupts macro-aggregates, increases aeration, stimulates microbial breakdown of soil organic C (SOC) (Reeves 1997), and accelerates soil organic matter decomposition and C loss from soil to the atmosphere as CO_2. In consequence, vineyard soils in La Rioja have a low soil organic matter content (< 10 g kg^{-1}) (Peregrina et al. 2010a)

Recently, the use of cover crops has been studied in La Rioja as a strategy to reduce the excess vigor of grapevines and to improve must and wine quality (Perez-Álvarez et al. 2015). In these studies, in La Rioja, it has been found that cover crops in the short term (4 years) can increase SCC with rates in the order of 1.5 Mg C ha^{-1} year^{-1} and with a high degree of stratification (Peregrina et al. 2010b). It has also been shown that the cover crops increase soil microbial activity and soil respiration (Peregrina et al. 2014a, 2014b; Peregrina 2016). However, there is very little information on how the SCC evolves over time and when the maximum level of SCC in equilibrium will be reached at different depths in agro-systems such as vineyard with cover crops under Mediterranean climatic conditions.

In addition, recent studies using models in Mediterranean climatic conditions indicate that the most promising practice was introducing cover crops in woody cropping systems, with an increase of 0.44 Mg C ha^{-1} yr^{-1} during the first 20 years (Pardo et al. 2017). These estimates are very valuable in encouraging the change from tillage to cover crops in Mediterranean vineyards, but it is also necessary to obtain field data to monitor the increase of SCC on the medium and long term to verify these estimates.

Therefore, the objective of our work was to study the SCC, its increase and stratification with respect to tillage in the medium term (5 to 8 years after the implementation of a cover crop) in a vineyard with climate and soil representative of La Rioja winegrowing area.

2. Materials and Methods

The experiment was established in 2004 at the farm “Finca La Grajera” property of La Rioja region government, NE Spain (42°26′34″ N; 2°30′53″ W). Experimental plots were situated at mid slope, facing east with a gradient of about 10.2%. Soil was classified as loam, mixed, thermic Typic Haploxerept according to the USDA soil classification (Soil Survey Staff 2014) and contained 230 g kg^{-1} clay, 433 g kg^{-1} silt, and 337 g kg^{-1} sand, 9.3 g kg^{-1} OM, 149 g kg^{-1} carbonates; pH was 8.62 and electrical conductivity 0.17 dS m^{-1} in the Ap horizon (0-20 cm).

The climate in the area is semiarid according to the UNESCO aridity index (UNESCO 1979), with heavy winter rains and summer drought conditions. For the period 2005-2012, the average annual precipitation was 434 mm, average annual temperature was 13.0 ºC, and average annual potential evapotranspiration (FAO-Penman) was 1,129 mm. Soil moisture regime according Soil Taxonomy (2014) was xeric.

The vineyard selected was established in 1996 with *Vitis vinifera* L. ‘Tempranillo,’ grafted on 110-R rootstock, which had a planting density of 2998 vines ha^{-1}, spaced 1.15 m within and 2.9 m between east–west facing rows. The vines were trained on the bush. During the 1996 to 2004 period, the soil management was conventional tillage with herbicide application in the vine line. Before the vineyard was established in 1996, a pasture–legume–cereal rotation was used.

The experimental layout was a randomized complete block design with two treatments, three replications per treatment, and one replicate per block. Each replicate (plot) had three rows with 60 vines in each, (69 m in length, 5.80 m in width). Two types of soil management between the rows were studied: (1) soil with conventional tillage between rows, which consisted of 15 cm deep soil tillage using a cultivator once every 4 to 6 weeks, as weed control during the grapevine growth cycle required (CT); (2) permanent cover crop of resident vegetation (RV), which was dominated by annual grass and forbs common to La Rioja vineyards, including *Bromus mollis* L., *Hordeum murinum* L., *Diplotaxis erucoides* (L.) DC., *Sonchus asper* (L.) Hill, *Sonchus oleraceus* L., *Veronica latifolia* L., *Conyza canadensis* (L.) Cronquist., and *Papaver hybridum* L. The vegetation was mowed to a height of 10-15 cm using a flail mower twice a year, before vine bud break (first week of February) and at vine flowering (end of May or first week of June). The cover crop residue after mowing was left on the soil. From the beginning of 2004, none of the treatments were fertilized. In the CT and RV treatments, a 0.8 m wide herbicide strip was maintained in the rows using herbicide (post-emergence, glyphosate), to avoid problems in the maturation of the grapes due to excessive shade. The remaining management practices were similar in CT and RV treatments.

Soil sampling was carried out in June 2009 and June 2012 at 0-5, 5-15, and 15-25 cm depths. In each plot, six soil cores were taken to make a composite sample representative of each plot and depth. At 0-5 cm depth, soil cores were taken with stainless steel cylinders (height: 51 mm, diameter: 50 mm, volume: 100 cm^3), and at 5-15 and 15-25 cm depths with an Edelman type auger. Once in the laboratory, the 0-5 cm soil cores were extracted carefully and were subdivided into 0-2.5 cm and 2.5-5 cm depth increments. The bulk density was determined at depths of 0-5, 5-15 and 15-25 cm with the ring method (Grosman and Reisnch 2002), taking 2 rings per depth. Soil organic C was determined by the Walkley and Black wet oxidation method (Nelson and Sommers 1982).

Concentrations of SOC were converted to mass per unit area for a 0-2.5, 2.5-5, 5-15 and 15-25 cm soil depth by calculating the product of SOC concentration, the bulk dry density, the thickness, and the percentage of soil < 2 mm.

Statistical procedures were carried out with the software program Statgraphics Plus for Windows (1998). Three way-ANOVA for SCC was carried out considering factors Tillage (CT, CV), Depth (0-2.5, 2.5-5, 5-15 and 15-25 cm) and Year (2009, 2012). For SCC increase and SCC annual increase, two way-ANOVA was carried out considering two factors, Depth and Year. To determine pair-wise differences by post-hoc tests, one-way ANOVA was performed at each depth using the least significant difference (LSD) multiple range test calculated at $P < 0.05$.

3. Results

The three way-ANOVA analysis indicated that the factors tillage (CT vs. RV) and soil depth and the interactions between factors tillage x depth, depth x year and tillage x depth x year significantly affected SOC. In addition, two way-ANOVA analysis showed that the factor depth significantly affected the SCC increase, while the factors depth, year and the interaction depth x year significantly affected the SCC annual increment rate (**Table 1**).

Soil Carbon content in CT (**Table 2**) was similar to SCC found in vineyards soil from La Rioja under conventional tillage (Peregrina et al. 2010a).

In the 0-2.5 and 2.5-5 cm soil depths at year 2009, RV increased SOC compared to CT. In the 0-2.5, 2.5-5 and 5-15 cm soil depths at year 2012 RV increased SOC compared to CT (**Table 2**).

The SCC increase with cover crop compared to tillage was higher in 2012 than in 2009, but only in the 2.5-5 cm soil depth (**Table 3**). In 2009, the SCC increase was greater at the soil surface (0-2.5 cm soil depth) than the 2.5-5 cm and 5-15 cm soil depths. In addition, at 2.5-5 and 5-15 cm soil depth the SCC increases were greater than at 15-25 cm soil depth.

In 2012, there were no significant differences in the SCC increase between 0-2.5 cm and 2.5-5 cm soil depths. However, the SCC increment at 2.5-5 cm and at 5-15 cm was similar and higher than the SCC increment at 15-25 cm soil depth.

The SCC annual increment was lower in 2012 than in 2009 at the soil surface (0-2.5 cm) and the whole thickness of studied soil (0-25 cm) (**Table 3**). In 2009, the SCC annual increment was greater at 0-2.5 cm than at 2.5-5 cm and at 5-15 cm soil depths, which were in turn higher than at 15-25 cm soil depth. Finally, in 2012, the SCC annual increase at 0-2.5 cm was higher than at 5-15 cm. At 2.5-5 cm and 5-15 cm soil depths, the SCC annual increase was higher than that at 15-25 cm depth.

Table 1. Three-way ANOVA for SCC considering tillage, depth and year and two-way ANOVA for SCC increase and annual SCC increment rate considering depth and year

3-ways ANOVA		2-way ANOVA		
Factors	**SOC (% C)**	**Factors**	**SCC increase ($Mg\ C\ ha^{-1}$)**	**SCC annual increment rate ($Mg\ C\ ha^{-1}$)**
	P value		*P* value	*P* value
Tillage	< 0.001	Depth	< 0.001	< 0.001
Depth	< 0.001	Year	0.151	< 0.001
Year	0.759	Depth x Year	0.104	< 0.001
Tillage x Depth	< 0.001			
Tillage x Year	0.396			
Depth x Year	0.032			
Tillage x Depth x Year	0.031			

Table 2. Soil organic C in the tillage and cover crop treatments at the 0-2.5, 2.5-5, 5-15 and 15-25 cm soil depth, after 5 and 8 years respectively of cover crop establishment

			Soil depth			
Year	**Years after cover crop establishment**	**Treatment**	**0-2.5 cm**	**2.5-5 cm**	**5-15 cm**	**15-25 cm**
			Soil organic Carbon (% C)			
2009	5 years	Tillage	0.61±0.05†bA ‡	0.60±0.03bA	0.63±0.05aA	0.61±0.03aA
		Cover crop	2.45±0.17aA	1.43±0.08aB	0.73±0.04aC	0.64±0.01aC
2012	8 years	Tillage	0.61±0.05bA	0.60±0.01bA	0.59±0.03bA	0.57±0.01bA
		Cover crop	2.21±0.10aA	1.81±0.12aB	0.76±0.03aC	0.64±0.01aC

† Standard deviation; ‡ Different lowercase letters indicate significant differences between treatment for each soil depth and different uppercase indicate significant differences between soil depth for each treatment (Least significant difference) *P* < 0.05.

Table 3. Increments of SCC under cover crop respect to tillage in years 2009 and 2012, after 5 and 8 years respectively of cover crop establishment

Year	**Years after cover crop establishment**	**SCC increment respect to tillage ($Mg\ C\ ha^{-1}$)**				
		0-2.5 cm	**2.5-5 cm**	**5-15 cm**	**15-25 cm**	**0-25 cm**
2009	5 years	7.23±0.97†aA‡	3.39±0.45bB	2.85±0.09aB	0.41±0.39aC	13.88±1.81a
2012	8 years	6.32±0.94aA	4.84±0.75aAB	3.74±1.42aB	0.93±0.51aC	15.83±3.29a

† Standard deviation; ‡ Different lowercase letters indicate significant differences between years for each soil depth and different uppercase indicate significant differences between soil depth for each year (Least significant difference) *P* < 0.05.

Table 4. Annual increment rate of SCC under cover crop respect to tillage in years 2009 and 2012, after 5 and 8 years respectively of cover crop establishment

Year	Years after cover crop establishment	SCC annual increment rate respect to tillage (Mg C ha^{-1} year^{-1})				
		0-2.5 cm	**2.5-5 cm**	**5-15 cm**	**15-25 cm**	**0-25 cm**
2009	5 years	1.45±0.20†bA‡	0.68±0.09aB	0.57±0.02aB	0.08±0.08aC	2.78±0.28a
2012	8 years	0.79±0.12aA	0.60±0.09aAB	0.47±0.18aB	0.12±0.06aC	1.98±0.41b

† Standard deviation; ‡ Different lowercase letters indicate significant differences between years for each soil depth and different uppercase indicate significant differences between soil depth for each year (Least significant difference) $P < 0.05$.

4. Discussion

Regarding C stratification in soil under cover crops, our data are similar to C stratification found in vineyard soil with different cover crops (Peregrina et al. 2010b; Peregrina et al. 2014a).

In addition, the results showed that SCC increase occurred with differentiated accumulation rates depending on soil depth (**Table 4**). For example, after 5 years, the SCC increment at 0-2.5 cm was approximately 2 fold that at 5-15 cm, 2.5 fold that at 5-15 cm and 18 fold that at 15-25 cm. After 8 years, the SSC increment at 0-2.5 cm was approximately 1 fold that at 5-15 cm, 2 fold that at 5-15 cm and 7 fold that at 15-25 cm

Therefore, taking into account this stratification by sampling at smaller soil depth intervals would allow a better understanding of the SCC increment dynamics in the soil than sampling at greater thickness intervals.

After 8 years with a cover crop, the SCC increase was lower than after 5 years. This SCC increase after 8 years was of the same order as that found by Franzluebbers et al. (2001) after the transformation from crop to pasture.

In addition, this SCC increment after 8 years was much higher than the 0.5 Mg C ha^{-1} reported in annual cereal systems under Mediterranean climate in Spain (Hernanz et al. 2009).

Our data confirmed the high potential of SCC increase under cover crops in semiarid vineyard at the medium term (8 years). Moreover, they were in agreement with models indicating that woody cropping systems with cover crops had the highest SCC increase rates in Mediterranean Spain (Pardo et al. 2017).

Annual SCC increase rates in our study were in the range found by the meta-analysis of studies with cover crop in woody crops (olive, almond and vine) under Mediterranean climatic conditions (Vicente-Vicente et al. 2016), however our results were higher than the average values found by Vicente-Vicente et al. (2016).

Moreover, the lower SCC annual increment after 8 years compared to 5 years of the cover crop establishment, according to Vicente-Vicente et al. (2016) that found for the studies with a duration of less than 6 years an annual SCC increase rate of 1.22 Mg C ha^{-1} yr^{-1}, a value which was 1.7 times higher than that observed in studies carried out over 6 to 10 years (0.72 Mg C ha^{-1} yr^{-1}).

Under our conditions, the lower SCC annual increase after 8 years was due to the fact that SCC did not increase at the soil surface since 2009, and although at 2.5-5 cm soil depth there was an increment in SCC, the accumulation rate was much lower than at the surface (0-2.5 cm).

The lower accumulation rate at 2.5-5 cm soil depth could be due to the fact that at this depth (2.5-5 cm) there would be less contribution of vegetal residues than at soil surface (0-2.5 cm), since only the roots would supply residues and not the aerial part of the cover crop.

Therefore, in view of our data, the SCC increase occurred in the subsurface soil (2.5-5, 5-15 and

15-25 cm) but with lower rates than those found in the surface layer.

In consequence, the maximum SCC was not reached at 2.5-5, 5-15 and 15-25 cm soil depths. In the case of the soil surface (0-2.5 cm), there was no SCC increase after three years (2009-2012).

Consequently, at 2.5-5, 5-15 and 15-25 cm soil depths, it could not be established that the steady state in SCC was reached at these depths. Unlike at soil surface (0-2.5 cm), where there was no increase in SCC after three years (2009-2012), and therefore a steady state in SCC would have been reached.

5. Conclusions

At the medium term (8 years), a semi-arid vineyard with cover crop of resident vegetation had an increase of 15 Mg C ha^{-1} with an annual increment rate of SCC 2 Mg C ha^{-1} year^{-1}.

The stratification of SCC means that although at 0-25 cm soil depth there was no SCC increase from 2009 to 2012, there was an SCC increment 2.5-5 cm soil depth.

In consequence, the steady state for SCC would not have been reached at the medium term (8 years), so that the soil in the subsurface layers could continue to increase SCC but at lower rates than in the superficial zone (0-2.5 cm), since those subsurface layers receive fewer inputs of vegetal biomass.

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