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IMPACT OF SOIL TILLAGE AND LAND USE ON SOIL ORGANIC CARBON DECLINE UNDER MEDITERRANEAN CONDITIONS

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Abstract

Soils under Mediterranean climate conditions frequently have low to very low levels of soil organic matter (SOM), as a result of low biomass production under the predominantly rainfed conditions and the intensive tillage operations commonly practiced. In order to assess both short and long-term impacts of soil tillage and land use on soil organic carbon, two sets of experiments were performed. One consisted in the identification and soil analysis of 3 pairs of sites under different soil types and land use over 5 to 30 years; in the second experiment a long-term fallow area was repeatedly submitted to different types of soil tillage management (mouldboard plough + disc harrow; non-inversion tine cultivation; no-till) over 3 years. Soil texture, bulk density and SOM were analysed along the whole soil profile in the first experiment, whereas bulk density and SOM to a depth of 30 cm was measured before the first tillage operations and at the end of the observation period in the second experiment.

The results clearly indicate that tillage based land use, irrespective of the type of land use, caused a considerable decline in SOM content in the tilled soil layer. Very small and inconsistent differences in SOM between paired soil profiles were observed in the lower part of the profiles. In the second experiment with three types of tillage systems, SOM content decreased with tillage intensity. Avoidance of soil disturbance is an important step towards halting SOM decline under Mediterranean climate conditions.

Keywords: soil organic matter, soil tillage, land use, Mediterranean

Introduction

Soil organic carbon (SOC) changes in agricultural soils mainly occur because of soil management practices that alter the decomposition rates of soil organic matter and the amount of organic topsoil C that is lost through erosion (Bellamy et al., 2005; Ewert et al., 2005; Freibauer et al., 2004). Therefore, SOC is very sensitive to land-use changes, both in terms of losses or gains (Smith, 2008; Bell et al., 2011). Further, land-use change is considered the second greatest cause of CO_2 emissions after fuel consumption (Watson et al., 2000).

Soils under Mediterranean climate are known to present low levels of organic carbon (Romanya and Rovira, 2011). Climatic effects, mainly warm and wet autumns and springs, lead to high mineralization rates of the organic matter, which, associated to low biomass production under rainfed conditions, intensive soil tillage used for crop establishment, straw removal and grazing of the stubble and soil erosion, are the main causes for the soil organic carbon depletion of Mediterranean cropland. Average soil organic matter (SOM) contents in the top layer frequently are around 1%. These low SOC contents affect crop and overall soil productivity in different ways; through a) reduced water infiltration and retention capacity, b) reduced cation exchange capacity and nutrient cycling efficiency, c) deficient soil structure and root growth. Furthermore, the frequent cycles of wetting and drying of the soil during the growing season favour silting and crust formation of the exposed soil layer leading to deficient gas exchange and plant emergence. In general, the extremely low SOM contents are responsible for the low resilience of Mediterranean soils to the frequent adverse conditions of scarce or excessive rainfall (Kassam et al., 2012).

In this study, integrated in a research project on the potential of no-till for carbon sequestration in agricultural soils, we also wanted to understand the medium and long-term effects of different land use on the potential accumulation/loss of organic carbon along the soil profile, and how tillage would affect SOM sequestered over a period of several years of grazed fallow.

Materials and Methods

The studies carried out for the purpose of the above described objectives consisted of two sets of experiments; one was based on the identification and analysis of adjacent areas under distinct land use over several years ('land use trial'), in the other trial we submitted a long-term extensively grazed fallow area to different types of soil tillage ('tillage trial'). Whereas the 'tillage trial' had been subject to rainfed conditions before and during the soil sampling period, two of the 'land use trial' sites had been under irrigation on the cultivated area. Climatic conditions at all sites are typically Mediterranean with an annual precipitation of around 550-600mm and an average annual mean temperature of around 16°C.

Land use trial

For the purpose of this trial we identified several "promising" locations in the Alentejo district in South Portugal, where we performed a previous soil sampling and an inquiry of the land owner regarding the land use history. Three sites were chosen for the detailed soil sampling and analysis, which were Barrocal, 10 km southwest of the district capital Évora (38°29'52.54"N; 8° 1'15.27"W), Oriola, about 35 km south of Évora (38°18'47.97"N; 7°49'45.23"W), and Comenda, 80 km northeast near the Spanish border (38°53'35.73"N; 7° 3'25.31"W). The distance between the paired soil profiles was less than 50 m at all trial sites. Following the above order, the soils at the 3 sites can be characterized as a stagnic Alisol, a haplic Regosol, and an epileptic Regosol, respectively. For each site and land use system a soil pit of about 1.5 m width was opened. Texture and chemical analysis were performed on composite soil samples taken for each layer. Average soil bulk density was determined from 5 undisturbed samples (100 cm^{-3}) per depth layer. Table 1 and 2 provide data on the soil physical parameters of the 3 paired sites. Whereas soil texture was analysed down to a depth of 70 cm, bulk density was determined only to the depth of 40 cm, subdivided in 10 cm layers. The extremely high stone content at the Comenda site did not allow the measurement of bulk density. For the calculation of the soil organic carbon stock in the top 40 cm layer we assumed an average bulk density of 1.5 Mg m^{-3} for both soil profiles at this site. For this site, the stone content was determined instead in order to perform the correction of the soil carbon stock based on the fine earth soil fraction.

Table 1 Soil texture of the three paired observation sites (in % of soil fraction < 2mm)

	Site→	**Barrocal**			**Oriola**			**Comenda**		
	Depth	**Sand**	**Silt**	**Clay**	**Sand**	**Silt**	**Clay**	**Sand**	**Silt**	**Clay**
Profile (P1) (without cultivation)	0-10	69,5	15,7	14,8	20,1	22,5	57,4	68,6	14,7	16,7
	10-20	68,2	15,9	15,8	20,5	22	57,5	71,4	13,1	15,5
	20-30	65,4	17,1	17,5	19,1	22,2	58,7	70,4	13,6	16
	30-40	62,7	16,1	21,1	19,7	21,5	58,8	71,6	14,2	14,2
	40-50	49,8	11,8	38,4	19,8	22,2	58	73,6	13,1	13,3
	50-60	51,9	13,4	34,7	20,8	21	58,2	72,6	13,9	13,5
	60-70	55,5	15,4	29,1	17,6	21,3	61,1	76,4	11,3	12,3
Profile (P2) (under cultivation)	0-10	69,8	14,5	15,7	31,1	24,1	44,7	76,2	11,6	12,2
	10-20	73,7	13,2	13,1	33,3	23,5	43,2	73,6	12,7	13,7
	20-30	68,2	12,3	19,5	31,3	23,7	44,9	72,6	13,3	14,1
	30-40	62,2	12	25,8	24,9	22,1	53	74,8	12,3	12,9
	40-50	48,2	14,1	37,7	29,7	21	49,3	78	9,8	12,2
	50-60	47,7	13,1	39,2	27	21,9	51,1	79,4	8,6	12
	60-70	47,7	13,8	38,5	24,9	22,2	52,9	80,9	8,6	10,5

Whereas the soil from the Barrocal site presented almost an identical soil texture composition for the different depths of both profiles, Oriola and Comenda showed slightly higher clay contents in the profiles without cultivation.

Table 2 Soil bulk density used for the calculation of soil carbon stocks as measured for the trial sites Barrocal and Oriola and assumed (*) for the soil fraction < 2mm at Comenda.

Site	Profile	Depth (cm)			
		0-10	10-20	20-30	30-40
Barrocal	P1 (not cultivated)	1.50	1.63	1.69	1.68
	P2 (cultivated)	1.53	1.59	1.74	1.68
Oriola	P1 (not cultivated)	1.26	1.29	1.28	1.33
	P2 (cultivated)	1.35	1.44	1.42	1.32
Comenda*	P1 (not cultivated)	1,50*	1,50*	1,50*	1,50*
	P2 (cultivated)	1,50*	1,50*	1,50*	1,50*

Table 3 presents the results the soil chemical analysis performed for the 3 observation sites, subdivided for the analysis of all parameters only for the top soil layer (0-30 cm), between profiles of the different land use systems.

Land use history of the area of both profiles at the Barrocal site was common until 2003 and consisted of a wheat-sunflower crop rotation, using until the early 90s the traditional tillage system based on the mouldboard plough once per crop rotation and disk harrow or tine cultivation for seedbed preparation. Later the mouldboard plough was replaced by the chisel. In 2003, a centre pivot was installed on this area, under which maize was grown as monocrop, established every year after mouldboard ploughing and disking (P (profile) 2). The corner areas outside the pivot were maintained as permanent pasture, grazed over winter until the next maize crop (P1).

Table 3 Some soil chemical parameters for the top layer of the three paired observation sites (0-30 cm) and for the subsoil based on composite soil samples for each site.

	Site→	**Barrocal**			**Oriola**			**Comenda**		
	Profile→	**P1**	**P2**	**P1/P2**	**P1**	**P2**	**P1/P2**	**P1**	**P2**	**P1/P2**
Parameter	**Depth (cm)→**	**0-30**	**0-30**	**30-60**	**0-30**	**0-30**	**30-60**	**0-30**	**0-30**	**30-60**
P_2O_5	(ppm)	76	22		8	12		338	310	
K_2O	(ppm)	60	44		78	80		244	400	
pH	(H_2O)	6,0	6,6		6,3	5,8		6,3	5,9	
CEC	cmol kg^{-1}	34,0	33,0	38,6	43,2	56,4	59,4	26,0	28,9	11,1
Ca^{++}	cmol kg^{-1}	3,7	3,7	10,2	20,9	13,8	24,6	4,8	2,7	2,3
Mg^{++}	cmol kg^{-1}	1,8	1,7	6,0	18,3	9,2	16,7	0,9	0,8	0,8
Na^{+}	cmol kg^{-1}	0,3	0,8	3,8	0,3	0,3	0,4	0,1	0,1	0,1
K^{+}	cmol kg^{-1}	0,1	0,1	0,2	0,2	0,2	0,2	0,5	0,6	0,5

At the Oriola site, the two profiles chosen were at the border of two different farms. One area had been used under the traditional “montado” (silvo-pastoral) system for decades, with a very occasional (every 7 to 10 years) cleaning of shrubs through superficial disking. The last cleaning operation was several years ago, which could be confirmed by the size of already existing vegetation. Across the border, the area of P2 had been under arable land use for at least 30 years, based on a rotation of different cereals and sunflower and regular mouldboard ploughing and disking for seed bed preparation. In 2001, the farmer adopted no-till for crop establishment, however continuing the removal of the cereal straw.

Similar to the Barrocal site, the profiles at Comenda were outside (P1) and inside (P2) a centre pivot area, cropped for 20 years under a maize monocrop, with the exception of the last 4 years when oats was grown twice. Due to the high stone content of the soil, the implements used for soil preparation were always the chisel and disk harrow. As the outside area had not been grazed, it was superficially disked 4 years ago, to supress the residues of the spontaneous vegetation accumulated over the years.

Tillage trial

For this trial we chose a small area of an experimental farm near Reguengos de Monsaraz (Central Alentejo/Portugal) that had not been used for arable cropping for more than 15 years. During this period the area was subject to occasional grazing only. The soil can be characterized as a haplic Luvisol. Within this area we selected two sub-areas in order to replicate the experiment of the effect of different tillage systems on the short-term response of soil organic matter (SOM). Each sub-area was divided in 3 plots of 15 x 4 m, where one plot was submitted to mouldboard ploughing (to a depth of 30 cm) and disking (10-15 cm), the second to chiselling (25 cm) and tine cultivation (10-15 cm), and the third one was left under fallow. No crop was established during the trial period and no further grazing occurred. The first tillage sequence was performed in autumn 2005 and repeated in spring and autumn of 2006 and 2007.

Soil sampling was carried out before the first tillage event in October 2005, and in April 2008. Each sub-plot was split into 3 blocks to repeat soil analysis within each sub-plot. Besides the initial and final soil sampling to a depth of 30 cm for the determination of SOM, a final measurement of soil bulk density was performed in order to calculate the carbon stock contained in the sampled soil layer. This determination was limited to one of the sub-areas (field 1), which showed a more uniform initial distribution of SOM.

Table 4 Soil bulk density in field 1 under the different soil management systems at the final soil sampling (2008).

Depth	Fallow	Chisel	Plough
0-10 cm	1.68	1.52	1.55
10-20 cm	1.64	1.71	1.59
20-30 cm	1.57	1.59	1.50

Results

Land use trial:

At the Barrocal site both soil pits showed a very similar soil texture profile along depth, i.e. a very clear increase in the clay content below 30 cm (table 1). Soil bulk density increased with depth but varied slightly and with no clear trend between land use systems (table 2). Regarding SOM distribution, a clear increase could be detected only in the first 5 cm of the area without cultivation when compared to the centre pivot area (figure 1a).

Despite the short distance between different land use areas (< 50m), the soil texture analysis of the two profiles at Oriola revealed a somewhat lower clay content for the area under cultivation, especially in the top layers. The moderate slope of this site and the consequent soil erosion could explain this difference to some extent. This site also showed a clearly higher soil bulk density of the 'arable' layer (0-30cm) in the soil under cultivation. SOM contents at the Oriola site were almost twice as high in the topsoil layer (0-10cm) when compared to Barrocal, and remained high throughout the profile. Differences between land use systems could be detected only for the topsoil layer (0-10cm) (figure 1b).

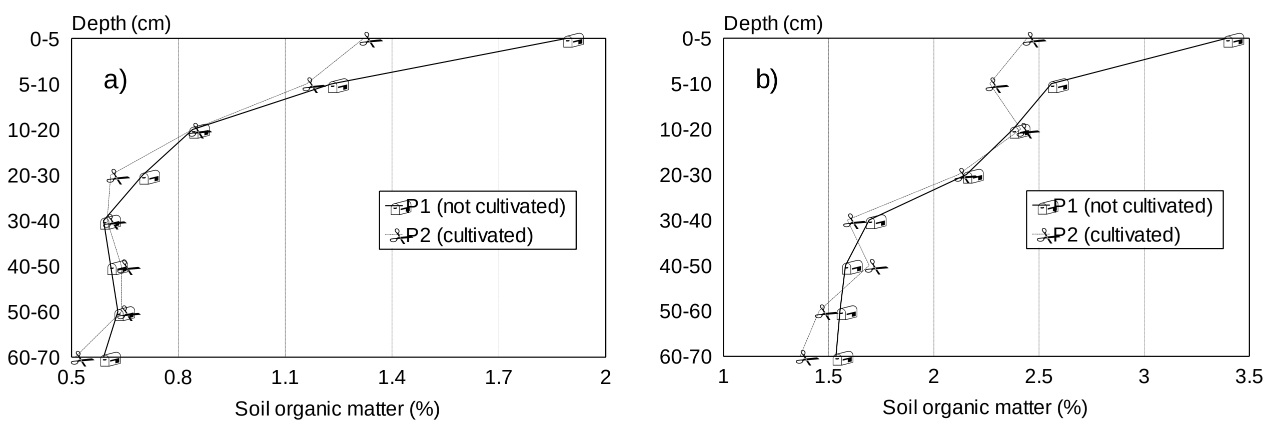

Figure 1 Soil organic matter content (%) along the soil profiles of the sites a) Barrocal and b) Oriola.

At the Comenda site the high stone content was even more pronounced under the non-cultivated system, but only for the top 20 cm soil layer. Accordingly, the big differences in SOM content detected for the fine earth fraction of the soil in this layer (figure 2a) shrank considerably when considering the whole soil (figure 2b).

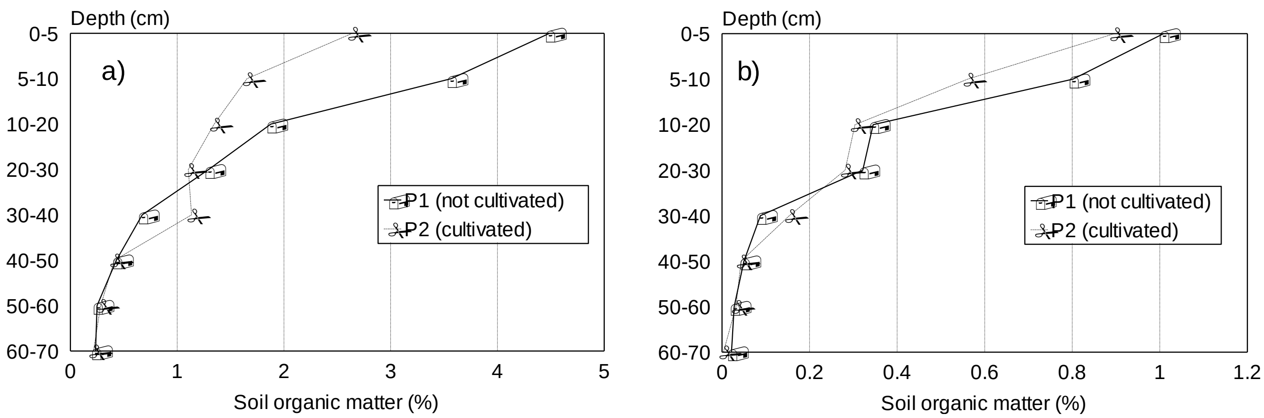

Figure 2 Soil organic matter content (%) along the soil profile of the site Comenda, a) with and b) without correction of the stone content.

Based on the measured (Barrocal, Oriola) and assumed (Comenda) soil bulk densities we calculated the amount of carbon contained in the top 40 cm of all soil profiles (table 5). Despite the short period of differentiated land use (5 years) at the Barrocal site, and the much higher biomass production (above and below ground) under the irrigated maize cropping system, the non-tilled area under spontaneous vegetation provided a higher carbon stock when compared to the intensively cultivated pivot area.

On the contrary, the long-term differentiated land use at the Oriola site, despite the clear differences in SOM content in the topsoil layer, did not result in consistent differences in terms of total carbon stock. The higher soil bulk densities, especially in the 10-20 cm and 20-30 cm soil layers with almost identical SOM contents under both cultivation systems compensated for the higher carbon stock measured in the top layer of the uncultivated “montado” system. In addition, the adoption of the no-till system for crop establishment during the past 7 years may already have contributed to invert the tendency of SOM decline under tillage farming (Franzluebbers, 2010; Varvel and Wilhelm, 2010).

Total carbon stock (0-40 cm) at the Comenda site was considerably lower than at Barrocal and especially Oriola, due to the extremely high stone content of this site. Assuming an average soil bulk density of 1.5 Mg m^{-3} for both land use systems and soil depth layers, the much higher SOM content in the top 20 cm of the uncultivated soil pit resulted in an overall higher carbon stock under this land use, despite a higher stone content in the top soil layer of the uncultivated area.

Table 5 Carbon stock (Mg C ha^{-1}) of the soil profiles at the different sites and under different land use.

	Barrocal		Oriola		Comenda	
Depth (cm)	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**
0-10	13.6	11.0	21.8	18.4	11.4	8.6
10-20	7.9	7.7	17.8	20.1	4.5	3.8
20-30	6.9	6.2	16.1	17.4	4.0	3.5
30-40	5.7	5.8	13.1	12.1	1.2	2.0
Sum (0-40)	**34.1**	**30.7**	**68.8**	**68.0**	**21.1**	**17.9**

Tillage trial:

Table 6 shows the results of the SOM analyses of the samples taken before the trial establishment in 2005 and in spring 2008, 6 months after the last tillage operations. Despite the small trial area of each field (sub-area) and the high number of soils cores taken for each composite sample, we detected some variation in the initial SOM contents, which was more pronounced in field 2 where the levels of SOM content were considerably higher, probably due to its lower location within the area. After the 5 tillage events as described above, the final distribution of SOM contents in the sampled soil layers reveals a clear effect of the tillage operations, especially an increase of SOM in the deepest soil layer monitored. Whereas the average SOM content increased in both fields under fallow, both ploughed fields revealed a lower average SOM content at the end of this short-term experiment. The chisel had no effect on the SOM content of the total soil layer analysed, but did affect its distribution between soil layers (figure 3a). Analysing both fields together, even under fallow, a decrease in the SOM content in the soil layer between 10 and 20 cm was registered. This was caused by a pronounced decrease only in field 2.

Table 6 Soil organic matter content (%) of both sub-areas of the tillage trial before the first tillage operation (2005) and at the end of the experiment (2008).

			Field 1			Field 2	
Year	**Depth**	**Fallow**	**Chisel**	**Plough**	**Fallow**	**Chisel**	**Plough**
2005	**0-10 cm**	1.27	1.41	1.27	1.81	1.79	1.97
	10-20 cm	0.90	0.92	0.90	1.61	1.52	1.69
	20-30 cm	0.78	0.79	0.76	1.13	1.03	1.22
	0-30 cm	0.98	1.04	0.98	1.52	1.45	1.63
2008	**0-10 cm**	1.43	1.21	0.94	2.11	1.84	1.64
	10-20 cm	1.00	1.14	0.92	1.38	1.33	1.64
	20-30 cm	0.83	0.87	0.90	1.28	1.23	1.38
	0-30 cm	1.09	1.07	0.92	1.59	1.47	1.55

Based on the soil bulk densities presented in table 4, determined during the final soil sampling in 2008, and assuming an initial bulk density for all tillage systems equal to the one determined under fallow, we calculated the changes in the soil organic carbon stock in the first 30 cm soil layer (figure 3b). The results confirm those obtained for the average SOM content for both fields (with the exception of the decrease in SOM in the 10 – 20 cm soil layer under fallow), i.e. a) a clear increase of the carbon stock under fallow, reducing with depth, b) a clear decrease in the very top soil layer under ploughing with an accumulation of SOC at the bottom of the arable layer, and c) a neutral behaviour of SOC stock under chisel with a transfer of SOC from the upper to deeper soil layers.

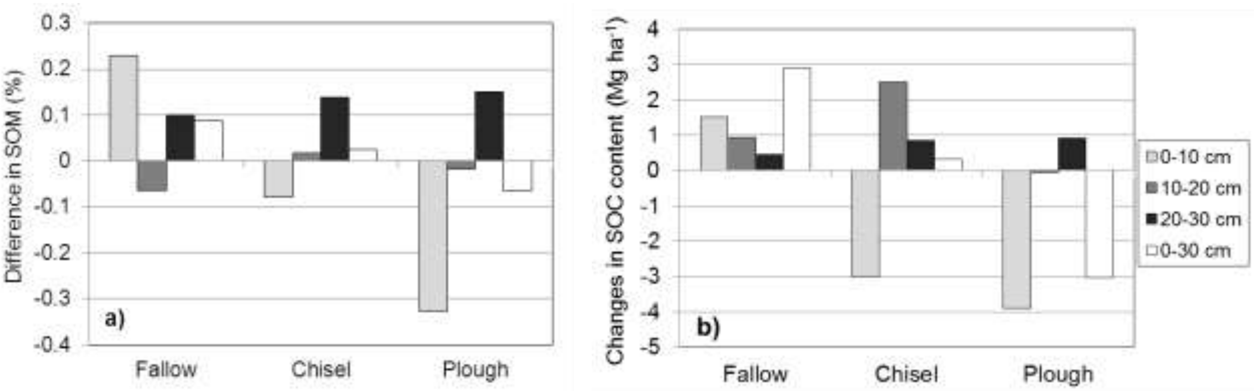

Figure 3 Changes in a) soil organic matter (%) (average of field 1 and 2) and in b) soil organic carbon (Mg ha^{-1}) in the top 30 cm (field 1 only) as affected by different soil tillage systems between 2005 and 2008.

Discussion and Conclusions

Both approaches analysed in this study tried to collect data on how differentiated land-use or soil management could affect SOC gains or losses under Mediterranean climate conditions. Although precise methods for measuring C in soil samples are well established (Conant et al., 2011), the problem of detecting changes in SOC induced by land use change or other management practices remains in the great spatial, vertical and temporal variability that determine SOC content (Ogle et al., 2003; Don et al., 2007; Poeplau et al., 2011). In this assessment we were aware about several insufficiencies of the methodology used both in terms of sampling design and the use of the simple bulk density method to calculate SOC stocks. Improved methods to overcome these difficulties are well documented in literature (Holmes et al., 2011; Yu et al., 2011; Zhang et al., 2011, Goidts et al. 2009; Lee et al., 2009; Poussart et al. 2004). However, the paired-site approach seems the most adequate one to obtain immediate results (Novara et al., 2012; Davis et al., 2004).

Whereas the short-term (Barrocal) and medium-term (Oriola, Comenda) land use changes provided expectable changes in terms of SOC and stocks, the differences obtained in the ‘tillage trial’ were surprising, both in what the gains under continuous fallow or losses under intensive soil tillage are concerned. Not surprisingly, in their meta-analysis on soil carbon stocks and land use change, Guo and Gifford (2002) found that it was the change from pasture to crop that provided the greatest losses (around 55-65%) observed of all land use changes under analysis.

Therefore, the results of both approaches seem to be in accordance with the findings from other authors. They also confirm that intensive, especially inversion tillage is responsible for the decline in SOC observed over decades of arable cropping (Schlesinger, 1986), and that the

SOC depleted soils under Mediterranean environments, even when abandoned (Raiesi, 2012), have a considerable potential to invert this decline.

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