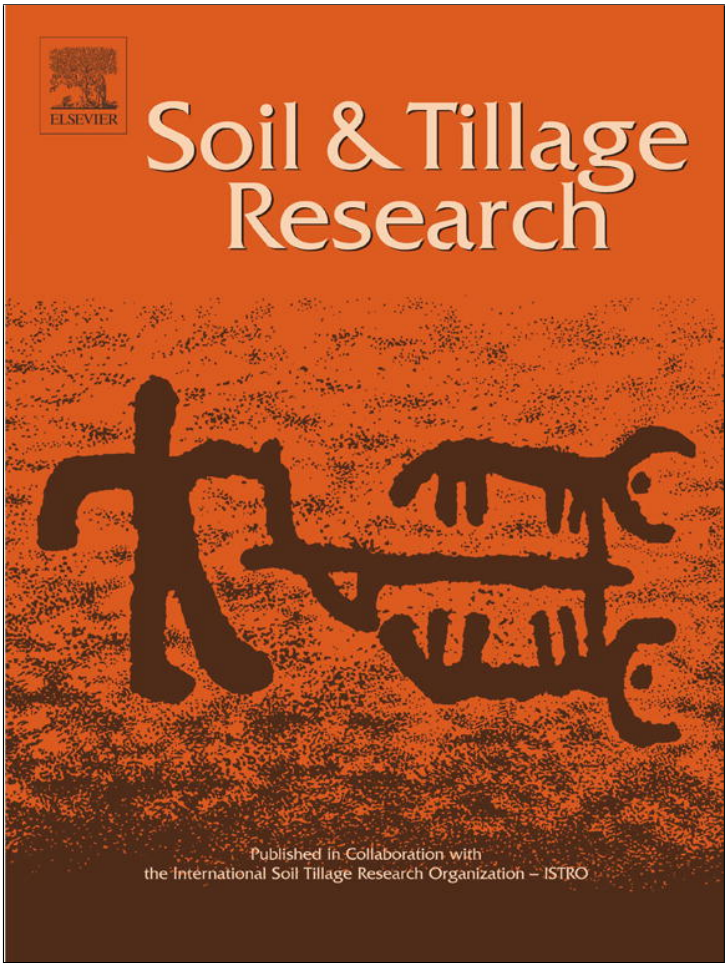
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Soil-carbon sequestration and soil-carbon fractions, comparison between poplar plantations and corn crops in south-eastern Spain

M. Sierra[a], F.J. Martínez[a], R. Verde[b], F.J. Martín[a,*], F. Macías[b]

[a] Soil Science Department, Faculty of Sciences, University of Granada, Campus Fuentenueva s/n, 18002 Granada, Spain
[b] Soil Science Department, Faculty of Biology, University of Santiago de Compostela, Rua Lope Gómez de Marzoa s/n, 15782 Santiago de Compostela, Spain

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ABSTRACT

The potential of soils as a sink of atmospheric carbon and the implications related to mitigate greenhouse-gas emissions are well recognized. The raising of tree crops on agricultural soils can augment soil-carbon sequestration more than do other agricultural uses such as corn crops. Thus, 6 plots with different durations of use as poplar plantation (5, 10, 20, 30, 50, and 100 years) were studied in comparison with 6 adjacent plots with corn crop. The carbon pool in poplar-plantation soils was positively correlated to the time of use at the three soil depths studied (0–20, 20–50, and 50–100 cm), the mean annual increase being 1.16 Mg C ha^{-1} year^{-1}. Poplar-plantation soils also increased the total carbon content in a more effective way because the duration of use was also correlated with the most recalcitrant carbon forms. Therefore, land-use change from corn crops to poplar-plantation soils is economically profitable as well as positive both for the total organic-carbon pool as well as for the efficiency of carbon sequestration by the increase of non-oxidizable forms in the soil.

1. Introduction

Soil organic matter can be defined as the complex mixture of different compounds coming from the plants and soil microorganisms (Stevenson, 1994). Humification processes produce metastable compounds that can remain in superficial systems for long periods. These processes are complex and currently no techniques are currently available to accurately describe the continuum of soil organic matter (Paul et al., 2006).

Soils play a central role in the global carbon cycle and constitute a large carbon reservoir (Quideau et al., 1998; Lorenz et al., 2006) 3.3-fold larger than the atmospheric-carbon pool and 4.5-fold the biotic pool (Lal, 2004a). This has stirred interest in finding methods to mitigate greenhouse-gas emissions, and soils have been suggested as a potential sink for atmospheric carbon (Feller and Bernoux, 2008; Maia et al., 2008; Mondini and Sequi, 2008).

The duration of sequestration can be separated into two components: flow duration and stock duration. Flow duration represents the time period of active sequestration, or the time in which annual changes in soil organic carbon occur. Stock duration represents the time period following active sequestration, and can be defined as the period of passive sequestration, or the time in which organic carbon remains sequestered (West and Six, 2007). In this way, it is necessary to develop agricultural and forestry techniques as well as soil-management practices oriented to encourage the long-term duration of carbon stock in the soil (Macías et al., 2004).

The main mineralization process of soil organic matter is the oxidation by abiotic mechanisms or biocatalysed by metabolic processes. Therefore, the first methods used to analyze soil organic matter were based on oxidative pathways, such as the potassium-dichromate method (Walkley and Black, 1934), and other oxidability sequences as methods using potassium-permanganate (Tirol-Padre and Ladha, 2004). The study of soil organic-matter stability is crucial because the oxidation processes trigger the change from organic to inorganic forms, implying the emission of CO_2 to the atmosphere, which was defined by Lundergard (1927) as “soil respiration”.

Now, the global emission of CO_2 from soils is recognized as one of the largest contributors to global carbon fluxes, and small changes in the magnitude of soil respiration could have momentous effects on the CO_2 concentration in the atmosphere (Schlesinger and Andrews, 2000). Deforestation and conversion of natural ecosystems to an agricultural one constitute major sources of the increasing atmospheric CO_2 concentration (Lal, 2004b). When soils are disturbed through cultivation, their soil organic-matter content declines because of the change in the decomposition conditions—soil aeration, destruction of soil aggregates, and moisture content—leading to greater rates of soil respiration. Improved management and alternative land use for agricultural soils could potentially bolster the role of soils as a CO_2 sink.

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* Corresponding author. Tel.: +34 958 248537.
E-mail address: fjmartin@ugr.es (F.J. Martín).

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With rising concern about the climatic consequences of greenhouse-gas emissions, worldwide efforts are being made to augment carbon sequestration and reduce CO_2 emissions. Afforestation of agricultural soils can help comply with the Kyoto protocol (Article 3.3) by increasing carbon sequestration. There is mounting interest in planting tree crops on agricultural land as an energy feed-stock. Energy crops are a carbon-neutral energy source for the portion of biomass harvested; however, there may be an additional carbon sequestration belowground that could help ameliorate increases in atmospheric CO_2 concentration (Hansen, 1993). Carbon sequestration resulting from incremental forest management, afforestation, and reforestation are eligible for receiving carbon credits from the Kyoto protocol (UNFCC, 1998). Organic-carbon sequestration in poplar-plantation plots is high, reducing CO_2 in the atmosphere and thereby lowering the use of fossil fuels, and adds an appreciable amount of C to the soil, helping to mitigate climate change (Deckmyn et al., 2004; Teklay and Chang, 2008). Hansen (1991) reported that soils in poplar plantations in the north-central United States sequestered 24 Mg C ha^{-1} more than adjacent soils under corn crops after an average of 15 years.

The present work studies the differences between the amounts of organic carbon fixed in the soils of the alluvial plain of Granada (Spain) under poplar plantations in comparison with soils under corn crops. The aim is to establish the differences in the amount and stability of the soil carbon as a mechanism to assess the efficiency in carbon sequestration by these soils.

2. Materials and methods

The study area is located in the alluvial plain of Granada (Spain), in the municipality of Santa Fe (30S 435860-4117155). This area contains fertile soils under irrigated conditions, and is located in the geological basin of Granada, which is surrounded by unirrigated lands. This is a post-orogenic basin closed on all sides except for the west and formed by an alluvial plain crossed from east to west by the Genil river, one of the main tributaries of the Guadalquivir river. The climate is typically Mediterranean, characterized by mean annual precipitation of 385 mm, occurring mainly during autumn and winter, with the summer being notably dry. Mean monthly temperatures ranges from 5 °C in winter and 23 °C in summer, with a mean annual value of 13 °C.

The soil type in all cases was haplic Regosol (calcaric) (ISSS-ISRIC-FAO, 2006) with slight variation in soil properties and constituents. The soils have fine textures that progressively become coarser with proximity to the river, but without statistically significant differences in depth either in soil fractions or in mineralogy. The proximity to the river also determines the depth of a phreatic layer, producing the presence of grey and reddish-brown colours heterogeneously distributed in the soil profile related to the hydromorphic conditions [endogleyic Regosol (calcaric) and Gleyic Fluvisol (calcaric); Aguilar et al., 2006].

In general, the soils in the study area are deep with a high water-holding capacity (>100 mm), high cation-exchange capacity (>15 $cmol_{(+)}\,kg^{-1}$) and the exchangeable complex saturated in basic cations. The pH is slightly alkaline (pH = 8) and the $CaCO_3$ content is high (40%) throughout the soil profile (Simón et al., 1997). The organic-carbon content in the surface horizon varies depending of the soil use, being below 2.5% in poplar plantations and below 2.0% in corn crops, registering mean values of C:N ratio of 13 and 12, respectively. In general, they are usually described as fertile soils.

Soils in 6 poplar-plantation plots in the alluvial plain of the Genil river were studied. The soil type and topography were very homogeneous in all the study plots, and poplar was *P. x euramericana NNDV clone* in all cases. Due to the intense agricultural activity in the area, there were no natural soils next to the poplar plantations and, therefore, corn crops plots adjacent to each poplar plot were used for comparison purposes. The poplar plots sampled had a minimum surface area of 100 × 100 m, and a minimum plantation age of 5 years. In each of the 6 plots with different ages of poplar plantation (5, 10, 20, 30, 50, and 100 years) and in the 6 adjacent plots with corn crop, 4 replicates of soil samples were taken after division of the plots in four similar parts (sub-plots) and taking one composite sample in the centre of each sub-plot. Each sample was obtained by the mixture and homogenization of four sub-samples taken from the corners of a 4 × 4 m square, coinciding with the lanes of the plantation, and having one tree in the centre. Before the soil sampling the litter layer on the surface were removed, and a pit 50 cm wide and 100 cm deep was dug to take samples at three depths (0–20, 20–50, and 50–100 cm).

The soil management for the poplar plantation included soil conditioning for planting that consisted of crossed subsoiling followed by a pass with a cultivator, after which the cuttings were planted on 4 × 4 m centres. For the first two or three years, the weeds were eliminated by passes with the cultivator. No type of soil fertilization was applied and irrigation was by flood. Every 10–12 years, the trees were cut down and the process began again. Corn crop soils were tilled in autumn, followed by several passes with a cultivator to control weeds. After planting, a roller harrow was used for surface compaction to encourage germination and for the levelling of the land for even irrigation.

Bulk samples of mineral soil taken at each depth level, were thoroughly homogenized, air dried at room temperature and passed through a 2-mm sieve. For chemical analysis, an aliquot of the soil was ground in a ball mill. Total carbon (C_T) and nitrogen (N_T) were analyzed by a LECO® TruSpec CNHS. The carbonate content, as the main inorganic-carbon source, was determined by gas volumetry following the method of Barahona et al. (1984). Organic carbon was estimated by the difference between total carbon and the inorganic carbon estimated from the soil-carbonate content. Soil bulk density was determined by a gravimetric method in which a known volume of undisturbed soil sample was dried and weighed. Soil bulk density allows the calculation of the total organic-carbon pool in soils with poplar plantations and corn crops. Carbon fractionation values were derived by oxidation with 33 mM $KMnO_4$ (Tirol-Padre and Ladha, 2004) and 333 mM $KMnO_4$ (Blair et al., 1995) and by wet oxidation adding 10 ml $K_2Cr_2O_7$ 0.4N to 0.15–0.8 g of soil sample and blank sample and titring the excess of $K_2Cr_2O_7$ with $FeSO_4{\bullet}7H_2O$ 0.1N, according to the method of Walkley and Black (1934) and modified by Tyurin (1951). For the determination of the fractions oxidizable with $KMnO_4$, soil samples containing 15 mg C, calculated from the known total C content, were weighed into 30-ml plastic screw-top centrifuge tubes and 25 ml of 33 or 333 mM $KMnO_4$ were added to each vial. Soil and blank samples were shaken for 1 h and centrifuged for 5 min at 2000 rpm and the supernatant was diluted 1:250 with deionized water. Standards were prepared by adding 0.6, 1.0, 1.4, 1.8, and 2.0 ml of 33 and 333 mM $KMnO_4$, respectively. The absorbance of the diluted samples and standards were read on a spectrophotometer at 565 nm.

Carbon oxidized by 33 mM $KMnO_4$ was termed very easily oxidizable carbon (C_{VEO}); the difference between carbon oxidized by 333 mM and 33 mM $KMnO_4$ was termed easily oxidizable carbon (C_{EO}); the difference between carbon oxidized by $K_2Cr_2O_7$ and 333 mM $KMnO_4$ was termed oxidizable carbon (C_O); and the difference between total carbon and carbon oxidized by $K_2Cr_2O_7$ was termed non-oxidizable carbon (C_{NO}).

Differences of soil organic-carbon fractions, total organic carbon, and bulk density in soil depth and between different ages of poplar plantation were tested by one-way analysis of variance (ANOVA) and Tukey's test ($p < 0.05$). The variables were tested to the normalized Shapiro–Wilk normality test and to Bartlett's homogeneity test of variance. Spearman correlation coefficient was used to analyze the relations between variables. Statistical analyses were made using a Statistical Package for Social Sciences (SPSS® for Windows©, Ver. 15.0.1, Chicago, IL).

3. Results and discussion

The selected soils showed slight variation in the main properties and constituents (Table 1). Texture varied somewhat between plots, this parameter being considered important in the physical protection of the organic-matter compounds, promoting higher and more effective retention of organic carbon in soils (Lützow et al., 2006). The correlation analysis between the total organic carbon and the different textural fractions according to their oxidizability in the soils had positive relationships with the fine fractions and negative with the coarse, although the correlations were not significant in any case ($p > 0.05$). This absence of significant correlation between texture and organic carbon, and the homogeneity of other parameters (e.g. pH and calcium carbonate) allowed a meaningful comparison between plots.

The mean organic-carbon content in the poplar-plantation soils was higher than in the corn crops (Table 2). It is well known that the soil organic matter declines in soils under agriculture conditions, depending on the type of crop and soil management. In the comparison between the poplar plantation and corn crops, this difference was significant ($p = 0.014$) only in the surface samples (0–20 cm) but not in the deeper soil samples. This data is also supported by the positive significant correlation ($p < 0.05$) between the soil organic-carbon content and the age of the poplar plantation. This correlation was statistically significant at the three depths studied, although between 0–20 cm and 20–50 cm, the increase (slope) was 2.5-fold higher than in samples at 50–100 cm depth (Fig. 1).

Soil bulk density increases in samples according to the soil depth, although this increment was more pronounced in the corn crop soils than in the poplar-plantation soils. This difference may be related to the different soil management, because in the corn crops the continued tilling increased porosity in the surface layer but compaction in the subsurface samples. Below 50 cm depth,

Table 1
Main soil parameters analyzed according to the soil use, time, and depth.

Depth	Soil use	Clay (%)	Silt (%)	Sand (%)	$CaCO_3$ (%)	pH	Bulk density ($g\,cm^{-3}$)
0–20 cm	CC	30.2 *ab* (3.6)	43.1 *ab* (5.0)	26.7 *bcd* (8.0)	21.1 *a* (3.3)	7.6 *a* (0.1	1.218 *a* (0.051)
	(P5)	33.6 *b* (2.0)	43.6 *abc* (3.8)	22.9 *abc* (5.1)	18.3 *a* (1.0)	7.7 *ab* (0.1)	1.355 *b* (0.068)
	(P10)	33.9 *b* (4.1)	53.6 *c* (1.4)	12.6 *ab* (4.7)	19.0 *a* (0.8)	7.6 *a* (0.1)	1.287 *ab* (0.049)
	(P20)	24.7 *a* (0.8)	39.7 *a* (7.7)	35.4 *cd* (8.5)	21.0 *a* (0.8)	8.0 *b* (0.1)	1.350 *b* (0.066)
	(P30)	32.5 *b* (1.3)	44.1 *abc* (1.3)	23.5 *abc* (2.1)	20.8 *a* (0.5)	7.6 *a* (0.1)	1.327 *ab* (0.017)
	(P50)	25.2 *a* (0.3)	35.4 *a* (4.5)	39.4 *c* (4.4)	21.3 *a* (1.7)	7.7 *ab* (0.3)	1.293 *ab* (0.012)
	(P100)	36.0 *b* (2.9)	52.6 *bc* (5.6)	11.4 *a* (8.2)	22.0 *a* (1.8)	7.4 *a* (0.1)	1.247 *ab* (0.079)
20–50 cm	CC	29.2 *ab* (3.9)	42.0 *ab* (5.1)	28.7 *bc* (8.4)	20.5 *ab* (3.3)	7.6 *a* (0.2)	1.460 *c* (0.040)
	(P5)	33.3 *bc* (2.7)	43.6 *bc* (2.8)	23.2 *bc* (5.1)	15.3 *ab* (1.0)	7.7 *ab* (0.0)	1.362 *b* (0.029)
	(P10)	31.4 *bc* (3.8)	52.1 *cd* (1.2)	16.6 *ab* (4.5)	17.8 *a* (2.6)	7.7 *ab* (0.1)	1.317 *a* (0.022)
	(P20)	23.4 *a* (0.9)	40.5 *ab* (7.2)	36.2 *cd* (7.5)	21.3 *ab* (0.5)	8.0 *b* (0.1)	1.482 *c* (0.057)
	(P30)	32.7 *bc* (0.8)	46.2 *bcd* (2.7)	21.2 *ab* (2.6)	20.8 *ab* (0.5)	7.9 *ab* (0.1)	1.475 *c* (0.057)
	(P50)	24.3 *a* (1.2)	32.6 *a* (3.9)	43.2 *d* (5.5)	21.0 *ab* (2.2)	7.8 *ab* (0.2)	1.395 *bc* (0.050)
	(P100)	36.7 *c* (3.1)	53.3 *d* (5.0)	10.0 *a* (7.8)	23.3 *b* (3.9)	7.6 *a* (0.2)	1.352 *b* (0.049)
50–100 cm	CC	29.5 *ab* (4.1)	42.5 *abc* (4.6)	27.9 *abc* (8.1)	21.3 *a* (3.7)	7.7 *a* (0.1)	1.507 *a* (0.102)
	(P5)	34.3 *b* (1.9)	47.2 *abc* (7.5)	18.6 *ab* (9.1)	19.3 *a* (1.5)	7.8 *a* (0.1)	1.540 *a* (0.081)
	(P10)	29.7 *ab* (7.1)	49.9 *bc* (4.2)	20.4 *ab* (11.)1	19.3 *a* (1.5)	7.6 *a* (0.1)	1.492 *a* (0.043)
	(P20)	23.1 *a* (2.6)	38.8 *ab* (10.0)	38.1 *bc* (12.5)	20.5 *a* (0.5)	8.1 *b* (0.1)	1.547 *a* (0.012)
	(P30)	32.7 *b* (2.3)	46.9 *abc* (1.1)	20.4 *ab* (2.4)	20.5 *a* (1.3)	7.8 *a* (0.1)	1.507 *a* (0.103)
	(P50)	21.8 *a* (2.6)	35.9 *a* (7.4)	42.3 *c* (9.2)	22.0 *a* (0.8)	7.9 *ab* (0.2)	1.475 *a* (0.020)
	(P100)	36.9 *b* (4.6)	52.8 *c* (3.6)	10.2 *a* (8.0)	23.8 *a* (1.7)	7.8 *a* (0.1)	1.545 *a* (0.033)

CC, corn crop. P5, P10, P20, P30, P50 and P100: age of poplar soil use of 5, 10, 20, 30, 50, and 100 years, respectively. Mean values (St. D.). Italics indicate significant differences between soil use ($p < 0.05$).

Table 2
Values of the carbon forms for the poplar-plantation and corn crop soils at the three depth studied.

Depth (cm)		C_T	C/N	Pool C	C_{NO}	C_O	C_{EO}	C_{VEO}
		($g\,C\,kg^{-1}$)		$Mg\,ha^{-1}\,30\,cm^{-1}$)	($g\,C\,kg^{-1}$)			
Poplar								
0–20	Mean	0.231	13	85.89	0.074	0.096	0.033	0.029
	St.D.	*0.044*	*2*	*16.88*	*0.033*	*0.019*	*0.011*	*0.011*
20–50	Mean	0.163	12	68.22	0.075	0.055	0.022	0.012
	St.D.	*0.046*	*2*	*17.99*	*0.034*	*0.015*	*0.005*	*0.005*
50–100	Mean	0.117	10	53.26	0.059	0.035	0.016	0.006
	St.D.	*0.019*	*1*	*9.04*	*0.018*	*0.009*	*0.005*	*0.003*
Corn crops								
0–20	Mean	0.179	12	65.51	0.040	0.060	0.038	0.021
	St.D.	*0.059*	*2*	*22.78*	*0.015*	*0.026*	*0.011*	*0.011*
20–50	Mean	0.149	10	65.07	0.044	0.049	0.022	0.017
	St.D.	*0.061*	*2*	*25.69*	*0.025*	*0.018*	*0.008*	*0.010*
50–100	Mean	0.104	9	47.39	0.042	0.032	0.012	0.012
	St.D.	*0.007*	*1*	*4.03*	*0.007*	*0.002*	*0.005*	*0.004*

St.D, standard deviation. Total carbon (C_T); non-oxidizable carbon (C_{NO}); oxidizable carbon (C_O); easily oxidizable carbon (C_{EO}); very easily oxidizable carbon (C_{VEO}).

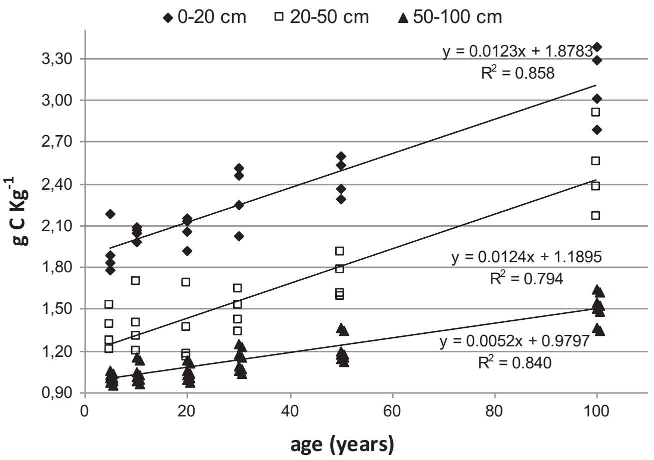


Fig. 1. Time course of the percentage in total carbon for the three depths sampled in relation to the age of poplar plantation.

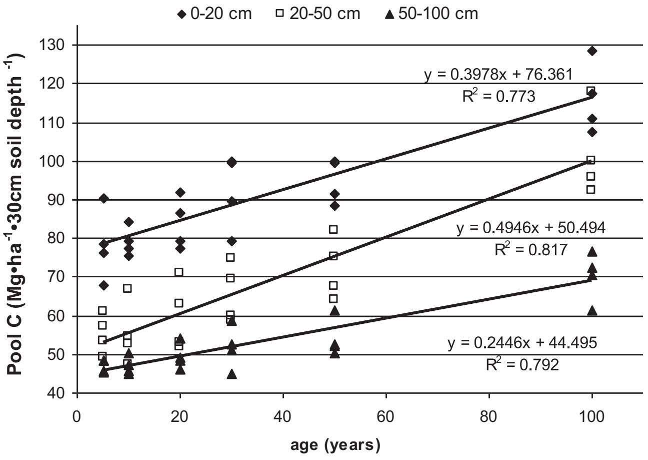


Fig. 2. Time course of the carbon pool for the three depths sampled in relation to the age of poplar plantation.

there were no significant differences in the soil bulk density according to the soil use and plantation age. Because of this variation in soil bulk density, the field-measured bulk densities were used to calculate the organic-carbon pool for both soil use considered and soil depth, by site. To normalize the organic-carbon pool for each level to a uniform soil volume, the organic-carbon-pool data are shown as organic-carbon mass per 30 cm soil thickness and hectare (Table 2). The trend of the organic-carbon-pool data was similar to the C_T percentage, with statistically significant differences ($p = 0.015$) in the surface samples (0–20 cm) but not in deeper samples (>20 cm).

The carbon pool positively and significantly correlated with the age of the crop in the poplar-plantation soils at all the depths sampled (Fig. 2). The comparison of the trend between the organic-carbon pool and the organic-carbon content in depth with respect to the age of the plantation (Figs. 1 and 2) shows a similar pattern at the three levels sampled, although the carbon pool in the uppermost 50 cm of the soil increased 1.9-fold quicker than at the shallowest depth.

Considering the organic-carbon pool and the age of the poplar plantation at the three depths sampled and compared with the corn crops (Table 3), there were statistically significant differences in the surface samples from 30 years of use in poplar-plantation soils. Between 20 and 50 cm depth the differences were statistically significant in relation to the corn crops from 50 years on, while at 50–100 cm these differences were significant from 100 years on. The different capacity of organic-carbon sequestration according to the soil use and management is highlighted mainly in the uppermost part of the soils (Tolbert et al., 2000; Castro et al., 2008), in agreement with our results. On the other hand, the ANOVA showed that at the soil surface of the poplar-plantation soils, the organic-carbon pool was consistently higher than in the corn crops. This may be due to the intense mineralization processes of the organic matter in the agricultural soils under traditional tilling (Lal, 2004a), the lack of shading by the vegetation canopy for several months of the year and the usual lack of surface mulch, which tended to increase soil temperatures compared to plantations and thus to augment carbon oxidation (Grigal and Berguson, 1998). In turn, poplar-plantation soils had a higher input of organic carbon via leaf litter, which forms an inherent part of the nutrient cycle, contributing a major source of soil organic carbon (Sayer, 2006); this litter also acts as mulch, cooling soil surface and reducing soil organic oxidation. Also, at >20 cm depth the carbon pool in the poplar soils was higher than in the corn crops after 20 years of use. Belowground, roots are a major source of soil carbon (Rasse et al., 2005) and they are protected by cooler temperatures and less aeration. The higher organic content reached by poplar-plantation soils at deeper levels could be due to the low root:shoot ratio of maize plants which results in a lower root carbon input, reducing soil organic-carbon content (Richter et al., 1990).

Therefore, the organic-carbon sequestration capacity of the poplar-plantation soils was higher than the corn crop soils, not only over the short term but also over the long term, increasing the carbon content even at the deepest levels. Taking into account the differences of the organic-carbon pool in all the soil profile (1 m depth) between the poplar-plantation and corn crop soils in relation to the age, and considering the content in corn crops as constant over time, we calculated the rate of mean increase in the organic-carbon pool to be 1.16 Mg C ha^{-1} $year^{-1}$ (Fig. 3). The rate of soil-carbon accumulation calculated was well within that measured by Garten (2002) but below rates reported by Hansen (1993), Blanco-Canqui (2009), and Gupta et al. (2009), and above rates predicted by Garten et al. (2010). Considering a soil-use change from the corn crop to poplar plantation, the increase in carbon sequestration would require a mean of 12 years to be effective.

Table 3
ANOVA and homogeneous subgroups (Tukey's test, $p < 0.05$) for the carbon pool (Mg ha^{-1} 30 cm^{-1}) in relation to the age of the poplar plantation and the use of corn crops.

	0–20 cm		20–50 cm		50–100 cm
CC	65.51 *a* (22.78)	CC	65.07 *a* (25.69)	CC	47.39 *a* (4.03)
P5	78.16 *a* (1.29)	P5	55.13 *a* (5.15)	P5	46.94 *a* (1.62)
P10	79.09 *a* (10.90)	P10	55.30 *a* (8.29)	P10	47.06 *a* (2.46)
P20	83.70 *a* (9.32)	P20	59.63 *a* (9.03)	P20	49.42 *a* (3.30)
P30	92.12 *ab* (4.86)	P30	65.59 *a* (7.74)	P30	51.80 *a* (5.70)
P50	94.45 *ab* (9.68)	P50	72.18 *ab* (8.03)	P50	54.14 *a* (4.98)
P100	116.15 *b* (13.49)	P100	101.45 *b* (11.39)	P100	70.17 *b* (6.36)

CC, corn crop. P5, P10, P20, P30, P50 and P100: age of poplar use of 5, 10, 20, 30, 50, and 100 years, respectively. Mean values (St. D.).

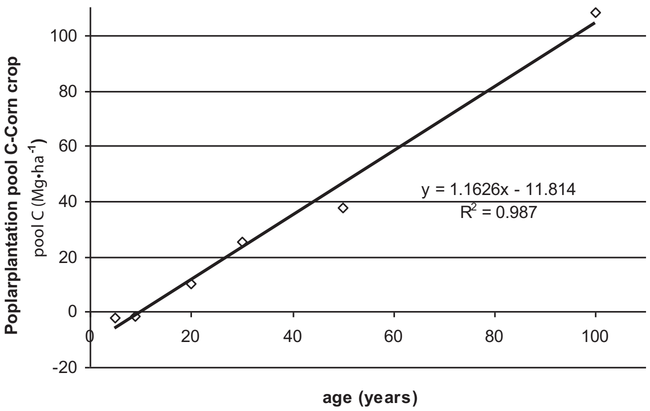
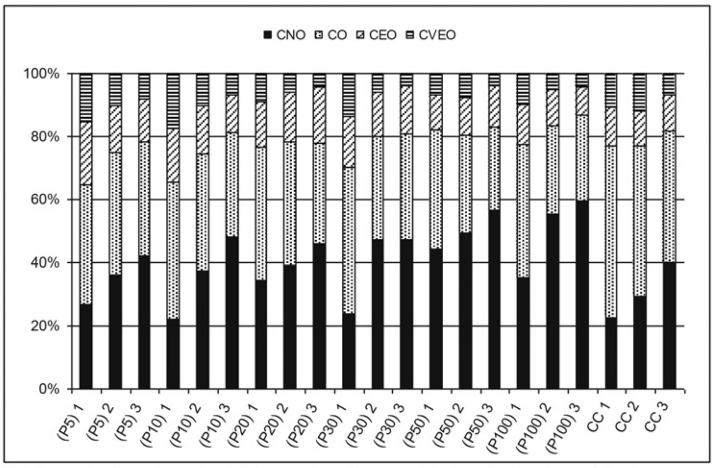


Fig. 3. Soil-carbon accumulation with hybrid poplar plantation age (calculation for 1 m soil profile).

The C:N ratios were comparable in poplar plantation soils, and ratios slightly decreased with depth due to progressive decomposition (Table 2). The C:N ratio is often the best predictor of the decomposition rate and indicator for the extent of decomposition, but may also be misinterpreted as a coincidental factor relative to gross biochemical composition and spatial arrangement of constituents in plant tissues (Magid et al., 2004; Jensen et al., 2005; Lorenz et al., 2006).

Total soil organic-carbon measurements have been widely used for monitoring soil organic matter. A drawback of using the total soil organic-carbon measurement alone is that soil organic matter changes gradually and thus short-term variations in organic carbon may be difficult to detect against a high background level. Chemical techniques can be used to determine the partitioning into different pools with variable turnover times and stability (Baldock et al., 2004).

In the present study, the distribution of the different fractions separated by the resistance to oxidation differed throughout the soil profile (Fig. 4). The ANOVA analysis shows a transition in depth with the increase in the non-oxidizable fraction (C_{NO}), which was statistically significant from 20 cm in depth (Table 4). This increase may be related to the higher recalcitrance of the organic carbon coming from the roots, the main source of carbon in depth. Chemical recalcitrance of plant litter is generally attributed to the aromatic compounds in the lignin, because microbial decomposition of these structures requires strong oxidation agents and only a limited number of soil microorganisms are able to completely mineralize lignin (Hammel, 1997). Lignin and other recalcitrant compounds such as tannins (Kraus et al., 2003), cutins and suberins (Tegelaar et al., 1989) show a higher content in roots than in shoots, reaching on average more than double in some species (Goering and Van Soest, 1970). In addition, the oxidizable fractions were higher in the uppermost 20 cm of the soils and significantly decreased with depth. The surface level (0–20 cm) significantly differed with respect to the deeper levels in relation to the organic-carbon fractionation, with the exception of the easily oxidizable fraction (C_{EO}), which was homogeneously distributed in the soil profile. This higher presence of the easily oxidizable fractions in the uppermost part of the soil should be related to the input of organic carbon coming from the litterfall, and, according to Gleixner et al. (2001) shoot tissues could decompose as fast as root tissue in soils but their transformation products would have shorter residence time in soils due to different chemical recalcitrance.



P5, P10, P20, P30, P50 Y P100: age of poplar use of 5, 10, 20, 30, 50, and 100 years, respectively. CC: Corn crop. 1, 2, and 3: 0-20, 20-50, and 50-100 cm soil depth.

Fig. 4. Mean values of the different fractions obtained in the oxidative fractionation for the three depth studied in relation to the age and type of crop; P5, P10, P20, P30, P50 and P100: age of poplar use of 5, 10, 20, 30, 50, and 100 years, respectively. CC: Corn crop. 1, 2, and 3: 0–20, 20–50, and 50–100 cm soil depth.

Table 4
ANOVA and homogeneous subgroups (Tukey's test, $p < 0.05$) for the relative carbon fractionation (%) in relation to the depth of the soil under poplar plantation.

Depth (cm)	C_{NO}	Depth (cm)	C_O
0–20	31.07 *a* (10.15)	0–20	41.61 *b* (6.68)
20–50	44.03 *b* (9.84)	20–50	34.30 *a* (6.75)
50–100	50.12 *b* (9.85)	50–100	31.18 *a* (8.35)
Depth (cm)	C_{EO}	Depth (cm)	C_{VEO}
0–20	15.42 *a* (4.32)	0–20	11.88 *b* (4.36)
20–50	14.16 *a* (2.99)	20–50	7.51 *a* (3.05)
50–100	13.37 *a* (4.40)	50–100	5.31 *a* (2.11)

(St. D.).

According to the age of the soil used for the poplar plantation, there was a significant increase ($p < 0.05$) in the relative %C_{NO} fraction, while on the contrary, the relative percentage of the oxidizable fractions (C_O; C_{EO}; C_{VEO}) significantly decreased ($p < 0.05$) in concentration. There were marked differences between poplar plantations and corn crops in terms of the soil-carbon turnover times. The C_{NO} was consistently lower at three depth levels in corn-crop soil than in poplar-plantation soil. Therefore, land use significantly affected both the total organic-carbon pool and chemically separated organic-carbon fractions.

The results in the poplar-plantation soils of the area suggest that there is high efficiency in the organic-carbon sequestration capacity over time both quantitatively, by the increase of the organic-carbon pool throughout the soil profile, as well as qualitatively, by the increase of more non-oxidizable forms of carbon.

4. Conclusion

The carbon pool in poplar-plantation soils increased over time with a mean annual value of 1.6 Mg C ha^{-1} $year^{-1}$, this increase being statistically significant in the surface samples (<20 cm) after 30 years of cultivation. The different organic-carbon fractions, separated by the differences in resistance to oxidation, indicate a significant increase in the non-oxidizable forms over time in relation to corn crops. Therefore, a land-use change from corn to poplars is economically profitable as well as positive both for the total organic-carbon pool as well as for the efficiency of carbon sequestration by the increase of non-oxidizable forms in the soil.

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