Catena 118 (2014) 84–90

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effect of cactus pear cultivation after Mediterranean maquis on soil carbon stock, $\delta^{13}C$ spatial distribution and root turnover

Agata Novara [a,*], Paulo Pereira [b], Antonino Santoro [a], Yakov Kuzyakov [c,d], Tommaso La Mantia [a]

[a] Dipartimento di Scienze Agrarie e Forestali, University of Palermo, Viale delle Scienze, Italy
[b] Environmental Research Centre, Mykolas Romeris University, Ateities g. 20, 08303 Vilnius, Lithuania
[c] Dept. of Soil Science of Temperate Ecosystems, University of Göttingen, Germany
[d] Dept. of Agricultural Soil Science, University of Göttingen, Germany

ARTICLE INFO

Article history:
Received 6 February 2014
Accepted 10 February 2014
Available online xxxx

Keywords:
$\delta^{13}C$ natural abundance
Soil organic matter
Spatial and depth distribution
Root turnover
Land use change
Carbon sequestration

ABSTRACT

Mediterranean ecosystems are characterized by nearly complete replacement of natural vegetation by intensive croplands and orchards leading to strong soil degradation. Organic carbon is usually accumulated in soils under maquis leading to partial regeneration of fertility for future agricultural use. The aim of this work was to investigate the effect of land use change from maquis to agriculture on soil organic carbon (SOC) stock and its spatial distribution in a Mediterranean system. Three Mediterranean land use systems (seminatural vegetation, cactus pear crop and olive grove) were selected in Sicily and analysed for soil C stocks and their $\delta^{13}C$. Total SOC and $\delta^{13}C$ were measured up to 75 cm soil depth within and between the rows of cactus pear and olive grove and along a similar transect in maquis, in order to evaluate the distribution of new and old C derived from roots. The land use change from Mediterranean maquis (C_3 plant) to cactus pear (CAM plant) lead to a SOC decrease of 65% after 28 years of cultivation, and a further decrease for 14% after 7 years after the change from cactus pear to olive grove (C_3 plant). Considering these SOC losses as well as the periods after the land use changes we calculated the mean residence time (MRT) of soil organic matter. The MRT of C under Mediterranean maquis was about 142 years, but was just 10 years under cactus pear. Root biomass of cactus pear was used for a new approach to estimate root turnover. The root turnover rate of cactus decreased along the soil profile from 7.1% per year in 0–15 cm to 3.7% in 60–75 cm soil depth. Along the transect, the average of root turnover values was highest in the middle of the intra-row. Root turnover and C input were correlated with SOC stocks to evaluate C sequestration potential of soils depending on land use and managements. We conclude that the SOC under maquis is higher and has longer residence time compared to permanent agricultural crops like cactus pear and olives.

1. Introduction

Mediterranean areas in recent centuries have been subjected to a substantial human impact, with intensive cultivation altering the structure and functions of soil, leading to erosion and degradation.

Alterations to ecosystem structure and function due to cultivation of natural area could have significant consequences for ecosystem biogeochemistry and potential implications for global C and N cycles and climate. Long-term experimental studies have confirmed that soil organic C (SOC) is highly sensitive to land use change in native ecosystems, such as the conversion from forest or grassland to agricultural systems, resulting in the release of 1.6 Pg C y^{-1} into the atmosphere and the loss of 40 Pg C from soil during the 1990s (Jenkinson and Rayner, 1977; Paul et al., 1997; Smith, 2008).

In Sicily many areas covered by natural vegetation were invaded by cactus pear. In fact, cactus pear easily grows in arid environment thanks to specialized photosynthetic system CAM (Felker and Russell, 1988; Oelofse, 2002). The high adaptability and fast biomass growth could increase C stock in semiarid native ecosystem. On the contrary no data on SOC accumulation are available on cactus pear cultivation and C isotopic signature ($\delta^{13}C$ natural abundance) of CAM species is useful to investigate cactus pear contribution to SOC change.

$\delta^{13}C$ natural abundance is widely used in ecological studies to investigate the dynamics of carbon (C) in soil and its responses to disturbance due to environmental changes or human activities (Desjardins et al., 2006; Novara et al., 2012a; West et al., 2010). In the last three decades, a strong research interest has risen on trace soil organic carbon (SOC) by $\delta^{13}C$ (Werth and Kuzyakov, 2010). The use of $\delta^{13}C$ signature is important to study sources of SOC and to quantify C flows as well as to determine SOC turnover rates (Boutton et al., 2009; Choi et al., 2001; Kuzyakov and Larinova, 2005). Recent approaches evaluate the variation in SOC stocks and their stability using natural difference in $\delta^{13}C$ isotopic

* Corresponding author. Tel.: +39 3206983438.
E-mail addresses: agatanovara@libero.it, agata.novara@unipa.it (A. Novara).

http://dx.doi.org/10.1016/j.catena.2014.02.002
0341-8162/

signature after C_3–C_4 or C_4–C_3 vegetation change (Blagodatskaya et al., 2011; Wittmer et al., 2009). Beside estimating SOC change and SOM turnover, $\delta^{13}C$ signature can be useful to detect the spatial variation of SOC in relation to C input (Bai et al., 2012), because $\delta^{13}C$ of SOC may reflect plant distribution and root development.

Very few studies have focused on the effect of land use change on turnover and availability of C in Mediterranean soils (Gavrichkova et al., 2010) and there is a need to detect which land use and management practices under semiarid condition are able to sequester atmospheric CO_2 and store C as well as maintain soil fertility.

Here we used the $\delta^{13}C$ to study the effect of land use change in a Mediterranean succession where seminatural vegetation (maquis, C_3 plant dominantly) was followed first by cactus pear cultivation (CAM) and then by olive grove (C_3). We combined the analysis of $\delta^{13}C$ in soil and roots with direct measurement of root biomass to develop an approach suitable to estimate C root turnover. Knowledge of root turnover and C input are important to evaluate the correlation between C input accumulation and SOC stock in order to study the ability of C sink of soils with different uses and managements.

The goals of this study were (i) to evaluate the effect of land use change on C stock in Mediterranean soil; (ii) to estimate the SOM turnover under natural vegetation and a cultivated soil, (iii) to examine the spatial relationship between $\delta^{13}C$, SOC and root growth, and (iv) to develop a method to estimate root C turnover.

2. Material and methods

2.1. Study and sampling area

The study was carried out in Montevago, in Sicily, Italy (37° 39′N, 12° 58′ E). The area is semi-arid (Thornthwaite and Mather, 1955) with a typical Mediterranean climate: most of the annual precipitation (570 mm) falls between October and February; monthly average temperatures range from 9.7 °C (January) to 25.6 °C (August). The soil in the study area is classified as Chromic calcixerert (Soil Survey Stuff, 1990). A detailed soil profile description is given in Table 1.

After an extensive analysis of a spatial–temporal airborne photography, a succession was selected on a plateau 390 m a.s.l, represented by maquis, olive grove and cactus pear (*Opuntia ficus-indica*) plantation (Fig. 1). Maquis is a typical Mediterranean natural vegetation with *Chamaerops humilis* L., *Olea europaea* L. var. sylvestris Brot., *Asparagus albus* L., and *Teucrium fruticans* L. The area was completely covered by maquia (C_3 photosynthesis) until 1977. Thereafter cactus pear (CAM photosynthesis) was planted after deep ploughing. In 2005 half of the cactus pear was converted to olive grove (C_3 photosynthesis).

Soil samples were collected under all land use systems, each 1 m along three 5 m length transects (in the intra-row), randomly chosen in each land use (Fig. 1). We termed point 0 as the sampling point in the middle of the intra-row, point +2 and −2 as the sampling points near the plant, and point −1 and +1 as the sampling points 1 m far from the olive and cactus pear plants. Each transect was replicated three times for each land use. Soil cores were taken using a cylinder (10 cm of diameter) up to 75 cm soil depth. The soil cores extracted were divided into soil depth layers of 15 cm. In total 225 soil samples (3 land use ∗ 5 sampling points ∗ 5 cm soil depth ∗ 3 replicates) were collected.

Table 1
Characteristics of soil profile according to USDA.

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	$CaCO_3$ (tot.)	pH (KCl)
Ap	0–40	17.0	54.9	28.1	28.8	7.2
Ass	40–65	15.1	48.9	36.0	27.6	7.2
ABssk	65–120	12.8	56.1	31.0	27.2	7.3
Bwss	120–180	9.3	49.5	41.2	26.0	7.5

2.2. Soil and root analysis

Soil samples were passed through 2 mm sieve, dried and stored before SOC and $\delta^{13}C$ determination. SOC content was measured using an elemental analyser (NA1500 Carlo Erba, Milan, Italy). Soil C stock (Mg ha^{-1}) was calculated as:

$$C_{Stock(Mg\ ha^{-1})} = BD * C_{con} * D * CF_{coarse} \quad (1)$$

where C_{con} is carbon content (%), BD is bulk density (Mg m^{-3}), D is depth thickness (m), and CF is a correction factor (1 − (gravel % + stone %) / 100). Bulk density was measured using the volume of the collected sample and the weight of dry soil in the sample (Blake and Hartge, 1986).

The $^{13}C/^{12}C$ ratio of bulk soil, root biomass of cactus pear, and olive and maquis biomass was measured using an EA-IRMS (elemental analyser isotope ratio mass spectrometer). The reference material used for analysis was IA-R001 (Iso-Analytical Limited wheat flour standard, $\delta^{13}C$ Vienna Pee Dee Belemnite (V-PDB) = −26.43‰). IA-R001 is traceable to IAEA-CH-6 (International Atomic & Energy Agency, cane sugar, $\delta^{13}C$ V-PDB = −10.43‰). IA-R001, IA-R005 (Iso-Analytical Limited beet sugar standard, $\delta^{13}C$ V-PDB = −26.03‰), and IA-R006 (Iso-Analytical Limited cane sugar standard, $\delta^{13}C$ V-PDB = −11.64‰) were used as quality control for the analysis. The C isotope results are expressed in delta (δ) notation and $\delta^{13}C$ values are reported in parts per thousand (‰) relative to V-PDB standard.

Natural abundance of $\delta^{13}C$ was used to determine the portion of C in SOM that was derived from the new crop and how much C remained from the previous crop in the soil. These portions were calculated by the mixing equation (Gearing, 1991):

$$\text{New carbon derived (Ncd)} = \frac{\delta^{13}C_{new} - \delta^{13}C_{old}}{\delta^{13}C_{biomass\ new\ species} - \delta^{13}C_{old}} \quad (2)$$

and

$$\text{Old Carbon derived (Ocd)} + 1 - \text{Ncd} \quad (3)$$

where Ncd is the fraction of C derived from new vegetation (cactus pear or olive grove), $\delta^{13}C_{new}$ is the isotope ratio of the soil sample, $\delta^{13}C_{biomass\ new\ species}$ is the isotope ratio of the colonizing species, and $\delta^{13}C_{old}$ is the isotopic ratio of the previous vegetation type (maquis).

Under cactus pear the Ncd corresponds to CAM–C portion and Ocd correspond to C_3–C portion. In soil under olive grove the C3–C portion is given by sum of new C input from recent olive biomass and the portion of SOC originated from ancient maquis.

Turnover of cactus pear biomass (mean residence time in years, MRT) was determined as a reciprocal of the rate constant (k) of first order decay (Eq. (4)) according to Balesdent and Mariotti (1996) and Dorodnikov et al. (2009).

$$k = \frac{-\ln(1 - \text{Ncd})}{\text{years since disturbance}} \quad (4)$$

The weight of cactus pear root was measured. After treatment of soil sample with sodium hexametaphosphate to facilitate dispersion of soil particles, roots were manually separated and only living root biomass was weighted. Root biomass was expressed in dry weight (g per volume of the cylinder) and C content and $\delta^{13}C$ were measured.

2.3. Calculation of root turnover for cactus pear

The soil $\delta^{13}C$ and biomass weight and MRT were used to estimate root turnover ($Root_t$) of cactus pear (Eq. (5)). The MRT of an element in a pool is defined as the average time the element resides in the pool at steady state.

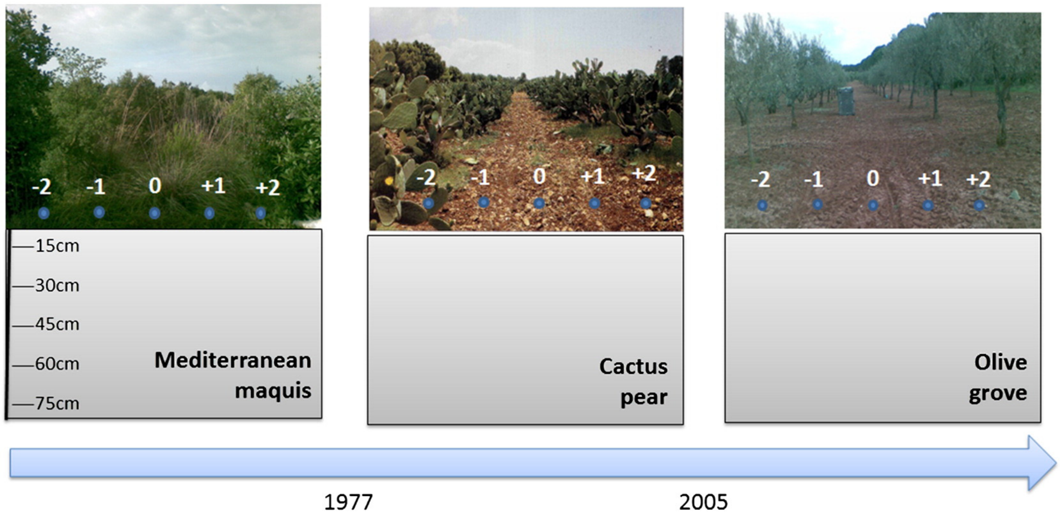

Fig. 1. Schematic representation of sampling points in the three land use systems.

Under cactus pear the amount of accumulated CAM–C, after the land use change from C_3 to CAM vegetation, corresponds to portion New Carbon derived from SOC.

$$\text{CAM–C} = \text{NCD} * \text{SOC} \tag{5}$$

In our case the CAM–C stock was the result of C input from root biomass only, as prune residues are removed from the field and used for animal feeding.

After a certain number of years the C input is:

$$\text{CI} = \text{C}_{\text{root}} * \sum_{n=1}^{\text{MRT}-1} e^{-k(\text{MRT}-n)} \tag{6}$$

C_{root} is the carbon content in roots ($g\ kg^{-1}$) that was measured using an elemental analyser (NA1500 Carlo Erba, Milan, Italy). C_{root} was calculated multiplying the weight of root (g root per kg soil) for C content of cactus pear root biomass. To calculate C input derived from root biomass a first order decay model was used (Six and Jastrow, 2002). MRT is the mean residence time calculated using the $\delta^{13}C$ isotopic signature shift in SOM after CAM–C_3 vegetation change.

Linking Eqs. (5) and (6) we obtained Eq. (7), considering that not all roots each year contribute to C input, but only a portion of roots ($Root_t$).

$$\text{NCD} * \text{SOC} = \text{C}_{\text{root}} * \sum_{n=1}^{\text{MRT}-1} e^{-k(\text{MRT}-n)} * \text{Root}_{\text{t}} \tag{7}$$

The $Root_t$ which represents the portion of root biomass that contributes to the annual C input is:

$$\text{Root}_{\text{t}} = \frac{\text{SOC} * \text{NewCderived}}{C_{root} * \sum_{n=1}^{\text{MRT}-1} e^{-k(\text{MRT}-n)}} \tag{8}$$

2.4. Statistical analysis

The data for SOC content, calculated new crop-derived C, and root weight were evaluated by analysis of variance (ANOVA) for a completely randomized block design. Differences between means were tested with the LSD test at $P < 0.05$. SAS statistical software was used (SAS Institute, 2001). Contour graphs on SOC stock were created using Surfer Software version 7.00.

3. Results

3.1. SOC stock and $\delta^{13}C$

SOC was lowest under olive grove, followed by cactus pear and maquis, with average content in 0–75 cm soil depth of 0.49 ± 0.06 g C kg^{-1}, 0.52 ± 0.09 g kg^{-1} and 1.2 ± 0.34 g kg^{-1}, respectively. SOC content, in 0–30 cm soil depth, decreased by 62% after the conversion from maquis to cactus pear plantation after 28 years. The SOC content decreased further by 14% after the conversion from cactus pear to olive grove after 7 years. In the deeper soil (30–75 cm), SOC decreased by 53% after the conversion from maquis to cactus pear, while SOC content was constant with cactus pear–olive grove land use change (Fig. 2). The $\delta^{13}C$ values were significantly different ($p < 0.005$) between the land use. The average of $\delta^{13}C$ in 0–75 cm soil layer was −26.5 ± 0.5‰, −22.9 ± 0.7‰ and −24.8 ± 0.4‰ for maquis (C_3), cactus pear (C_3–CAM) and olive grove (CAM–C_3 soil), respectively.

The effect of land use change (from C_3 to CAM and from CAM to C_3) on C stocks was highlighted by the estimates of C derived from maquis and from cactus pear (Fig. 3). After 28 years of cactus pear cultivation 73% of the C still had maquis origin, whereas in olive grove only 14% of C had a cactus pear origin after 7 years. After the conversion of cactus pear to olive grove, the CAM–C decrease was higher than C_3–C increase: it was lost 0.06 g kg^{-1} of CAM–C, while the gain of C_3–C was 0.04 g kg^{-1} (Fig. 4).

MRT was 10 times longer in maquis (142 years, overall average) than cactus pear (9.6 years, overall age). MRT values strongly increased with soil depth for both land uses due to more stability of organic matter in deep layer (Fontaine et al., 2007) and it was lowest in the middle of intra-row (Table 2).

3.2. Spatial pattern of SOC and $\delta^{13}C$

SOC content was significantly affected ($p < 0.05$) by spatial locations of sampling points in cactus pear and olive grove. The distribution of SOC content was homogeneous along the transect in maquis, especially in the upper 30 cm soil, being aboveground and belowground plant biomass uniformly distributed (Fig. 2a). Randomly distribution of plants under maquis is well demonstrated by observation of small and closed peaks in the first 0–15 cm soil layer. Higher SOC content (1.7 g C kg^{-1}) in the top soil (0–15 cm) and in the next layer (1.3 g C kg^{-1}) (15–30 cm) was recorded under maquis in comparison with the other land uses, that correspond to the layers with the highest amount of root biomass.

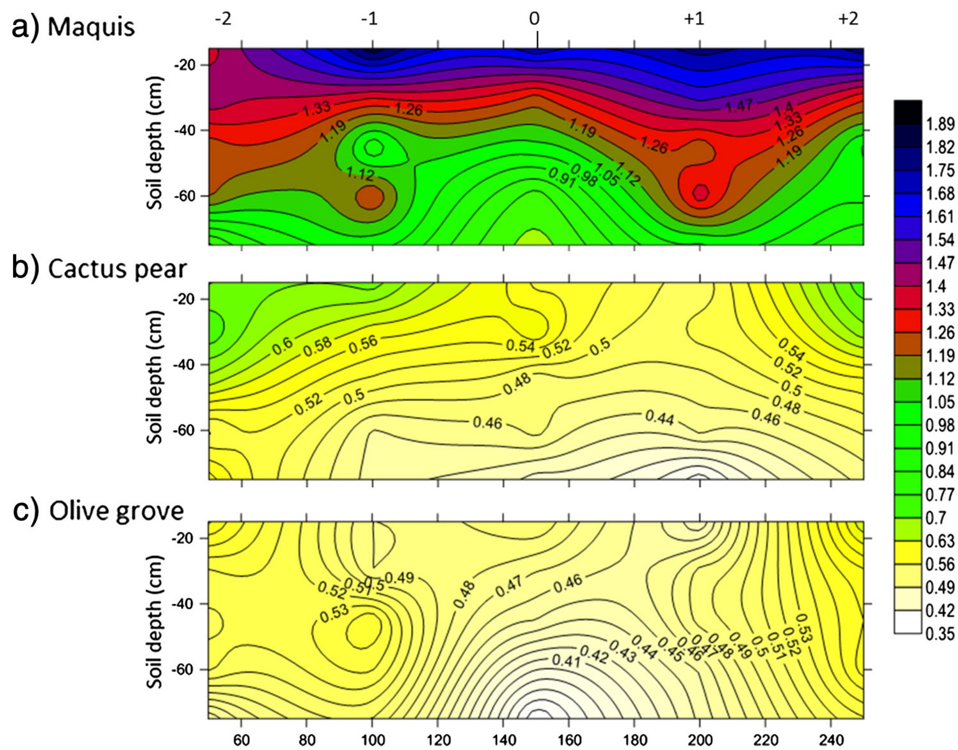

Fig. 2. Spatial and depth distribution (Y scale) of soil organic carbon (g C kg^{-1} soil) under Mediterranean maquis (a), cactus pear (b) and olive grove (c).

Under olive grove and cactus pear, SOC content was higher in the sampling points nearest the tree ring (+/−2) in comparison to the middle point of intra-row (point 0) (Fig. 2b,c). With regard to soil depth there were no significant difference in SOC content among the first three 15 cm layers, while SOC strongly decrease after 60 cm of soil depth under cultivated fields.

The values of $\delta^{13}C$ changed significantly with soil depth and distance from the tree rings. Under maquis $\delta^{13}C$ values were enriched with an increase of soil depth, while no significant differences were found along the transect (Fig. 5a). Under cactus pear the $\delta^{13}C$ was depleted with soil depth and in the sampling point −1/+1 (Fig. 5b). The depletion occurred because of C input from CAM root biomass. On the contrary to cactus pear, the $\delta^{13}C$ values under olive grove were depleted following root locations (Fig. 5c).

3.3. Cactus pear root biomass and turnover

The weight of roots was highest in the second soil layer (15–30 cm soil depth) (273 g root m^{-2}) followed by the first soil layer (0–15 cm soil depth) (260 g m^{-2}). There were no significant differences between the third and fourth soil layer, while root weight strongly decreased in 60–75 cm soil depth. With regard to the distribution along the intra-row, the values were highest in the sampling point +/−2 (275 g m^{-2}) and lowest in the sampling point +/−1.

The root turnover rate decreased along the soil depth from 7.1% per year in 0–15 cm to 3.7% in 60–75 cm soil depth (Fig. 6). In the intra-row the average of root turnover values was 5.3%, 6.4% and 4.4% for the sampling points +/−2, +/−1 and 0, respectively. The roots developed in the first layer of soil profile and 1 m far from the tree ring are composed by fine root and the turnover is therefore highest.

4. Discussion

4.1. Land use change and SOC

The SOC stock, apart from environmental parameters (climate, soil texture) is mainly affected by C input and soil management (Barbera et al., 2010; Six and Jastrow, 2002). In the analysed secondary succession, SOC stock decreased after the conversion of seminatural vegetation to cultivated soils. 28 years of cactus pear after maquis decreased the SOC content to 57%; and 7 years of olive grove after cactus pear decreased further SOC content to 5%. The SOC decrease was especially strong in the top soil (0–30 cm), which corresponds to the soil layer that receives more C input from the root biomass and litter under

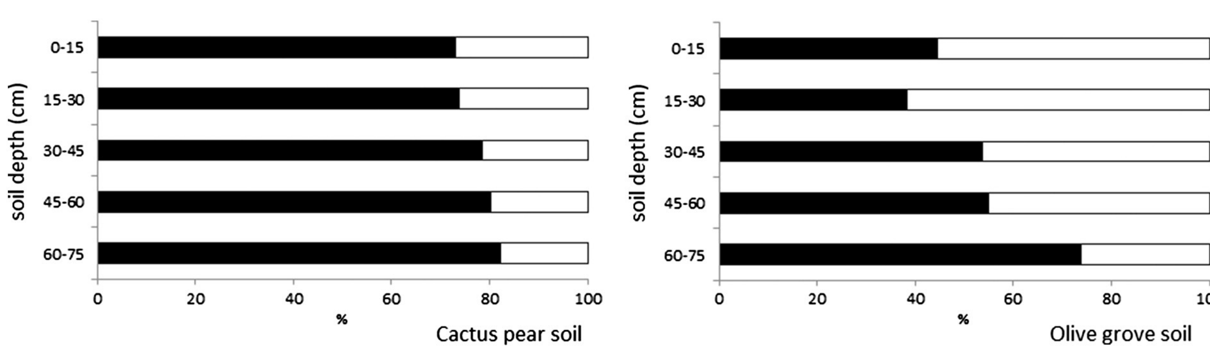

Fig. 3. C_3–C (white histograms) and CAM–C portions (black histograms) of SOC in cactus pear and olive grove soil.

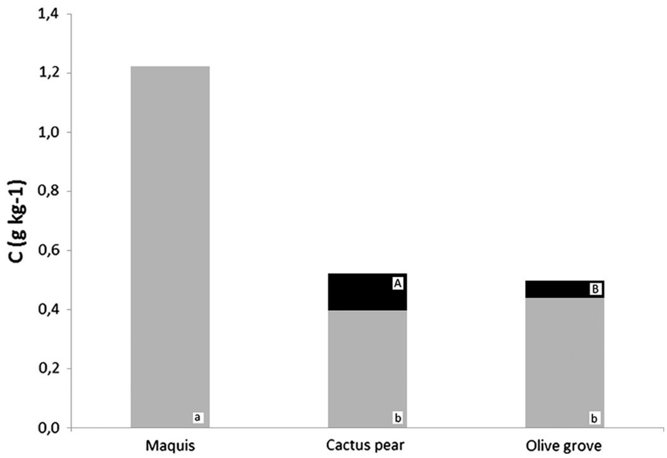

Fig. 4. SOC content in the three land uses and partitioning between C_3–C (grey histograms) and CAM–C (black histograms). Histograms with different letters are significantly different among samples ($P \leq 0.05$).

maquis and is mainly affected by the land use changes (Novara et al., 2012b). The decrease in C content by cultivation is the consequence of greater mineralization compared to natural soil and smaller C input. Continuous tillage of cactus pear soil and olive grove contributed to increase mineralization due to increasing aeration, breaking aggregates and more organic matter accessible to microbial activity (Solomon et al., 2002). Moreover, the C input into the soil under natural vegetation is from above and belowground biomass, while under cactus pear and olive grove the C input is only from roots, because all aboveground residues of cactus and olives were removed. The analysis of ^{13}C of SOM showed higher stability of the organic matter derived from C_3 plant than CAM plant. In cactus pear 76% of C had an origin from maquis after 28 years, while in olive grove 67% of C had an origin from cactus only after 7 years. Consequently we found a longer MRT for C under maquis than under cactus pear (Table 2). It is the consequence of different biomass characteristics between maquis and cactus pear. Other studies (Novara et al., 2012b) confirmed slow turnover rates of C under Mediterranean natural vegetation due to its highest content of lignin and siliceous compounds of many species of arid and semiarid environment.

4.2. SOC and root distribution

The δ^{13}C values were affected in cultivated soil mainly by root biomass input, and therefore they were enriched in cactus pear compared to maquis and depleted in olive grove compared to cactus pear. Under natural vegetation the δ^{13}C values were homogeneous along the transect, being homogenous the distribution of vegetation. The enriched δ^{13}C along soil profile can be attributable to SOM mineralization. According to our results other studies under C_3 vegetation reported a slight enrichment (1–2.5‰) during the litter decomposition to SOM phase at increasing depths (Gregorich et al., 1995; Nadelhoffer and Fry, 1988; O'Brien and Stout, 1978; Schneckenberger and Kuzyakov, 2007). This shift has been ascribed to a decrease of 1.5‰ in the δ^{13}C value of atmospheric CO_2 during the last 150 years: the Suess effect (Marino and McElroy, 1991), diagenetic isotope fractionation during decomposition (Nadelhoffer and Fry, 1988; O'Brien and Stout, 1978), or microbial respiration or fermentation leading to an enrichment of microbial products compared to plant material (Balesdent et al., 1993; Blagodatskaya et al., 2011; Macko and Estep, 1984).

Under cactus pear the lowest δ^{13}C values were found at 15–30 cm soil depth. The development of roots is especially in the top soil, but soil tillage for weed control, does not enable the growth of root in the top layer and facilitate the mineralization of SOM. Similarly in the olive grove the distribution of δ^{13}C was not homogenous, but the root growth was deeper than under cactus pear (Fig. 5c).

The distribution of SOC in soil profile permitted to analyse the SOC accumulation zone, while δ^{13}C was useful to study the growth of roots of new crops in secondary succession.

Table 2
Mean residence time (MRT) of organic C in soil under maquis and cactus pear.

	Depth	Sampling point				
	(cm)	−2	−1	0	1	2
Maquis	0–15	105	105(a)	85(a)	93(a)	148
	15–30	114	94(a)	96(a)	88(a)	186
	30–45	104	255(b)	104(b)	141(b)	138
	45–60	118	139(a)	244(c)	139(b)	138
	60–75	108	247(b)	259(c)	162(b)	139
Cactus pear	0–15	12	7(a)	7(a)	5(a)	17(b)
	15–30	11	4(a)	6(a)	5(a)	17(b)
	30–45	11	24(b)	8(a)	14(b)	8(a)
	45–60	11	9(a)	36(b)	8(a)	10(b)
	60–75	16	24(b)	52(c)	29(c)	15(b)

4.3. Estimation of root turnover

It is well documented that the use of Stable C isotopes can evaluate SOC stock change in a succession when C_3–C vegetation is followed by CAM–C vegetation and vice versa. The shift of δ^{13}C isotopic signature of SOM allows determination of stabilization and the mean residence time of C in soil. In this study we used these information to calculate the root turnover of cactus pear (Eq. (5)). The root turnover can be helpful to study carbon sequestration, budget and its dynamics (Hobbie et al., 2002). The belowground C input to soil does not correspond to the C content of the total root biomass; only a portion of this annually starts the decomposition and stabilization process of carbon cycle. Experimental data showed in fact a higher CAM–C content in root biomass than SOM. Therefore, we considered two adjustment factors in this C balance: (i) the turnover of root biomass and the mean residence time of SOM, since a portion of CAM–C of root origin is lost by mineralization processes. The knowledge of root turnover for a specific crop species, calculated by this method, can be used to estimate the annual root C input in C sequestration studies with permanent cultures or forests. We found that the annual C input by the roots of cactus is 0.03 g C kg^{-1} soil. The ratio between soil CAM–C content and C input accumulation after 28 years from plantation was 12%. This value describes the efficiency to sequester C derived from cactus pear root biomass and could be extended to aboveground biomass. Moreover, the calculated values of root turnover could be used in future studies to discriminate the SOC input originated from belowground or aboveground biomass in cactus pear land use. In our study, the absence of C input from above ground biomass gave an exact value of mean C annual accumulation from the roots.

5. Conclusions

This study analysed the effects of land use change on C stocks and distribution using natural ^{13}C abundance. Results of SOC, δ^{13}C as well as root biomass of cactus pear were used to develop an approach to estimate root turnover.

The major findings can be summarized as follows:

- soil under Mediterranean maquis accumulated more C than under cultivation with cactus pear or olive grove, and therefore the introduction of cactus pear is not recommended to increase C stock in semiarid soils;
- the mean residence time of SOM is higher under maquis (142 years) than cactus pear (9.6 years);
- SOC distribution is affected by aboveground and belowground biomass: SOC distribution is homogeneous under maquis, while it is heterogeneous under olive grove and cactus pear being correlated to root location along the rows;

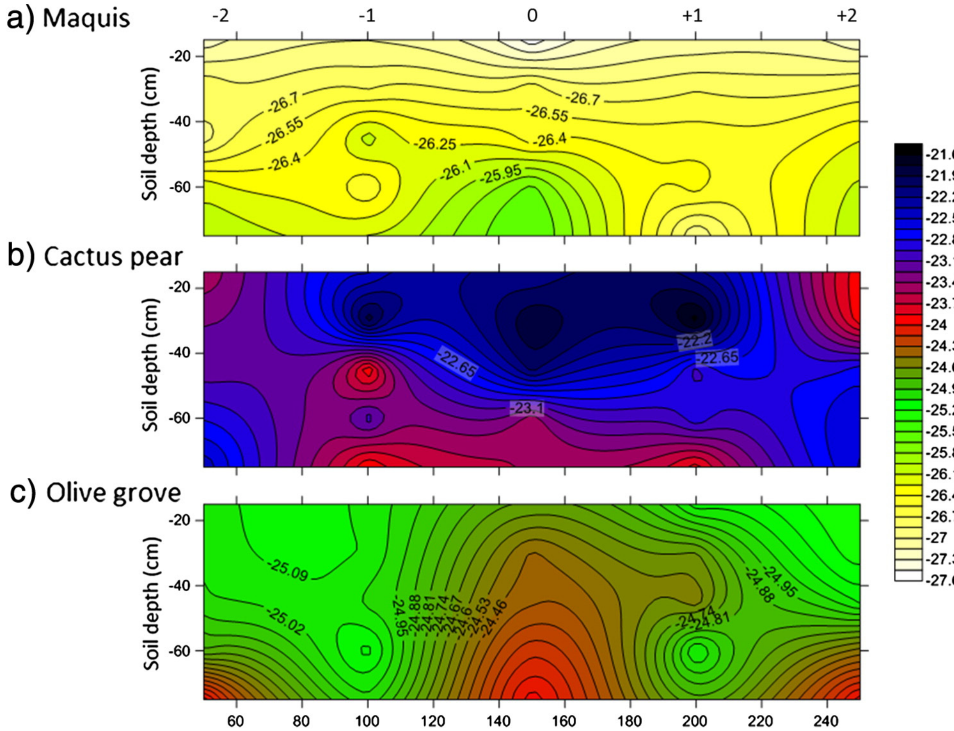

Fig. 5. Spatial and depth distribution of $\delta^{13}C$ of soil organic C under Mediterranean maquis (a), cactus pear (b) and olive grove (c).

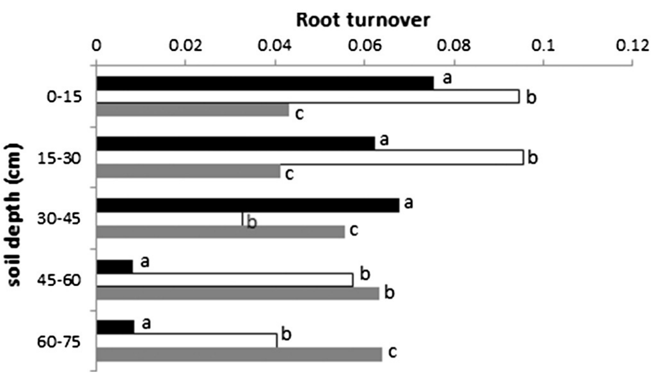

Fig. 6. Root turnover (%) along soil profile near the ring tree (grey histograms), in the sampling point +/−1 (white histograms) and in the middle of intra-row (+/−2 black histograms). Histograms with different letters are significantly different among samples ($P \leq 0.05$).

- the approach to estimate root turnover showed that values for cactus decreased along the soil profile from 7.1% per year in 0–15 cm to 3.7% per year in 60–75 cm soil depth;
- the estimated root turnover allows one to calculate the annual C input and evaluate the efficiency to store C for a specific land use.

References

Bai, E., Boutton, T.W., Liu, F., Wu, X.B., Hallmark, C.T., Archer, S.R., 2012. Spatial variation of soil $\delta^{13}C$ and its relation to carbon input and soil texture in a subtropical lowland woodland. Soil Biol. Biochem. 44, 102–112.

Balesdent, J., Mariotti, A., 1996. Measurement of soil organic matter turnover using ^{13}C natural abundance. In: Button, T.W., Yamasaki, S. (Eds.), Mass spectrometry of soils. Marcel Dekker, New York, pp. 83–111.

Balesdent, J., Girardin, C., Mariotti, A., 1993. Site-related $\delta^{13}C$ of tree leaves and soil organic matter in a temperate forest. Ecology 74, 1713–1721.

Barbera, V., Poma, I., Gristina, L., Novara, A., Egli, M., 2010. Long-term cropping systems and tillage management effects on soil organic carbon stock and steady state level of C sequestration rates in a semiarid environment. Land Degrad. Dev. 23 (1), 82–91. http://dx.doi.org/10.1002/ldr.1055.

Blagodatskaya, E., Yuyukina, T., Blagodatsky, S., Kuzyakov, Y., 2011. Turnover of soil organic matter and microbial biomass under C_3–C_4 vegetation change: consideration of ^{13}C fractionation and preferential substrate utilization. Soil Biol. Biochem. 43, 159–166.

Blake, G.R., Hartge, K.H., 1986. Bulk density, In: Klute, A. (Ed.), Methods of soil analysis, Part1, 2nd edition. Agronomy Monograph, vol. 9. American Society of Agronomy, Madison, WI, pp. 363–375.

Boutton, T.W., Liao, J.D., Filley, T.R., Archer, S.R., 2009. Belowground carbon storage and dynamics accompanying woody plant encroachment in a subtropical savannah. In: Lal, R., Follet, R. (Eds.), Soil Carbon sequestration and the greenhouse effect. Soil Science Society of America, Madison, WI, pp. 181–205.

Choi, Y., Wang, Y., Hsieh, Y.P., Robinson, L., 2001. Vegetation succession and carbon sequestration in a coastal wetland in northwest Florida: evidence from carbon isotopes. Glob. Biogeochem. Cycles 15, 311–319.

Desjardins, T., Folgarait, P.J., Pando-Bahuon, A., Girardin, C., Lavelle, P., 2006. Soil organic matter dynamics along a rice chronosequence in north-eastern Argentina: evidence from natural ^{13}C abundance and particle size fractionation. Soil Biol. Biochem. 38 (9), 2753–2761.

Dorodnikov, M., Blagodatskaya, E., Blagodatsky, S., Marhan, S., Fangmeier, A., Kuzyakov, Y., 2009. Stimulation of microbial extracellular enzyme activities by elevated CO_2 depends on aggregate size. Glob. Chang. Biol. 15, 1603–1614.

Felker, P., Russell, C.E., 1988. Effects of herbicides and cultivation on the growth of Opuntia in plantations. J. Hortic. Sci. 63 (1), 149–155.

Fontaine, S., Barot, S., Barre', P., Bdioui, N., Mary, B., Rumpe, C., 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature 450, 277–281.

Gavrichkova, O., Moscatelli, M.C., Kuzyakov, Y., Grego, S., Valentini, R., 2010. Defoliation decreases soil respiration and microbial activity in a Mediterranean grassland. Agric. Ecosyst. Environ. 136, 87–96.

Gearing, J.N., 1991. The study of diet and trophic relationships through natural abundance ^{13}C. In: Coleman, D.C., Fry, B. (Eds.), Carbon Isotope Techniques. Academic Press, San Diego, pp. 201–218.

Gregorich, E.G., Ellert, B.H., Monreal, C.M., 1995. Turnover of soil organic matter and storage of corn residue carbon estimated from natural ^{13}C abundance. Can. J. Soil Sci. 75, 161–167.

Hobbie, E.A., Tingey, D.T., Rygiewicz, P.T., Johnson, M.G., Olsyzk, D.M., 2002. Contributions of current year photosynthate to fine roots estimated using a 13C-depleted CO2 source. Plant Soil 247 (2), 233–242.

Jenkinson, D.S., Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. Soc. Am. J. 123, 298–305.

Kuzyakov, Y., Larinova, A.A., 2005. Root and rhizomicrobial respiration: a review of approaches to estimate respiration by autotrophic and heterotrophic organisms in soil. J. Plant Nutr. Soil Sci. 168, 503–520.

Macko, A., Estep, M.E.L., 1984. Microbial alteration of stable nitrogen and carbon isotopic compositions of organic matter. Org. Geochem. 6, 787–790.

Marino, B.D., McElroy, M.B., 1991. Isotopic composition of atmospheric CO2 inferred from carbon in C4 plant cellulose. Nature 349, 127–131.

Nadelhoffer, K.J., Fry, B., 1988. Controls on natural nitrogen-15 and carbon-13 abundances in forest soil organic matter. Soil Sci. Soc. Am. J. 52, 1633–1640.

Novara, A., Gristina, L., La Mantia, T., Rühl, J., 2012 aa. Carbon dynamics of soil organic matter in bulk soil and aggregate fraction during secondary succession in a Mediterranean environment. Geoderma. http://dx.doi.org/10.1016/j.geoderma.2012.08.036.
Novara, A., La Mantia, T., Barbera, V., Gristina, L., 2012b. Paired-site approach for studying soil organic carbon dynamics in a Mediterranean semiarid environment. Catena 89, 1–7.
O'Brien, B.J., Stout, J.D., 1978. Movement and turnover of soil organic matter as indicated by carbon isotope measurements. Soil Biol. Biochem. 10, 309–317.
Oelofse, R.M., 2002. Characterization of Opuntia ficus-indica cultivars in South Africa. Unpublished M.Sc. thesis, University of the Free State, Bloemfontein, South Africa. 128 pp.
Paul, E.A., Paustian, K., Collins, H.P., Schulthess, U., Robertson, G.P., 1997. Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL, USA.
SAS Institute, 2001. SAS/STAT, Release 8.01. SAS Inst., Cary, NC.
Schneckenberger, K., Kuzyakov, Y., 2007. Carbon sequestration under *Miscanthus* in sandy and loamy soils estimated by natural ^{13}C abundance. J. Plant Nutr. Soil Sci. 170, 538–542.
Six, J., Jastrow, J.D., 2002. Organic matter turnover. In: Lal, R. (Ed.), Encyclopedia of Soil Science. Marcel Dekker, NY, pp. 936–942.
Smith, P., 2008. Land use change and soil organic carbon dynamics. Nutr. Cycl. Agroecosyst. 81, 169–178.
Soil survey staff, SCS, 1990. Soil survey manual. United State Department of Agriculture, hand-book n.18, Washington DC.
Solomon, D., Fritzsche, F., Lehmann, J., Tekalign, M., Zech, W., 2002. Soil organic matter dynamics in the subhumid agroecosystems of the Ethiopian highlands: evidence from natural C-13 abundance and particle-size fractionation. Soil Sci. Soc. Am. J. 66, 969–978.
Thornthwaite, C.W., Mather, J.R., 1955. The water balance, 8. Laboratory for climatology publications in climatology, Centerton, NJ, pp. 1–86.
Werth, M., Kuzyakov, Y., 2010. ^{13}C fractionation at the root–microorganisms–soil interface: a review and outlook for partitioning studies. Soil Biol. Biochem. 42, 1372–1384.
West, J.B., Bowen, G.J., Dawson, T.E., Tu, K.P., 2010. Isoscapes: understanding movement, pattern and processes on earth trough isotope mapping. Springer, New York, NY.
Wittmer, M.H.O.M., Auerswald, K., Bai, Y.F., Schaufele, R., Mannel, T.T., Schnyder, H., 2009. Changes in the abundance of C3/C4 species of Inner Mongolia grassland: evidence from isotopic composition of soil and vegetation. Glob. Chang. Biol. 16, 605–616.