Cactus crop as an option to reduce soil C–CO₂ emissions in soils with declining fertility

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Accepted: 5 December 2017 / Published online: 22 January 2018
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Abstract

Arable soils tend to lose total organic carbon, thus contributing to the increase of CO₂ emissions into the atmosphere. This process has been occurring in large areas of Mexico cultivated with maize. Perennial species such as cactus (*Opuntia* spp.) and agave are grown in Mexico and other parts of the world, which can contribute to the maintenance of total organic carbon in the soil (TOC). Within this context, a study was designed to compare the patterns of emissions of C–CO₂ and TOC in a highland of central Mexico. The selected management systems were the following: (1) maize monoculture with conventional tillage and fertilization, (2) maize associated with *Vicia faba* and manure addition, (3, 4) cactus without and with composted manure mulching, (5) soil in oak-pine forest, and (6) maize fields under 4 years of soil fallow and without weed control. Measurements of CO₂ flux pulses and volumetric moisture were performed every 15 days at 5 points of each plot. The soil in oak-pine forest showed stable C–CO₂ emissions throughout the year, while under maize fields, emissions were unstable with several respiration peaks. The soil in cactus crop showed a very close pattern of forest soil respiration. The annual patterns of soil respiration were in agreement with the results of TOC recently reported for the same plots where soil respiration was measured. Here we show, for the first time, that TOC in cactus approached the reference line of soil under forest (6 g 100 g⁻¹), while in maize, we found a reduction greater than 50% of this value. Cactus crop represents an option in low-input maize for C–CO₂-reduced emissions in agricultural zones with declining soil fertility.

Keywords Soil respiration · Management systems · Land use change · Organic mulching · Perennial crops

1 Introduction

Due to the high demand for food, the conversion of forest ecosystems into agricultural systems has also increased worldwide, contributing to the loss of carbon (C) stocks in both vegetation and soil. Forests are systems that contribute to soil

total organic carbon (TOC) due to the diversity of interactions in which the living biomass of roots and decaying plant residues are involved (Schmidt et al. 2011). In recent decades, several studies have shown that agricultural soils have lost organic C, contributing to increase the CO₂ emissions. Land use change favors the exposure of the organic matter to degradation processes in which microorganisms are involved, which means increased rates of soil respiration and the loss of stored C (Paustian et al. 2000). It has been shown that constant restitutions of plant residues and nutrient inputs as fertilizers can ensure the preservation of TOC in soil (Janzen 2006; Johnston et al. 2009). The proposal and implementation of different management types of agricultural systems can exert an impact on reducing emissions, as well as on conserving or increasing soil C (Schmidt et al. 2011). In Central Mexico, it has been documented that management systems based on monoculture maize are affected at levels of organic carbon, which is aggravated by erosion in hillside soils. In order to reverse this trend, it has been demonstrated that the introduction of legumes associated with maize and organic

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matter inputs in the form of manure and plant residues have a positive effect on soil carbon storage recovering in the short and medium term (5 to 20 years; Etchevers et al. 2009). In the last decades, agricultural systems have been sought, such as those mentioned above, which contribute to maintain or improve the reserves of TOC, due to the pressure on the forest soils that has caused the loss of native TOC reservoir. The fall of organic carbon in the soil in low input systems such as maize and the need to reverse this process through a greater diversity of cultivated species must be accompanied by obtaining evidence on soil respiration patterns, in order to guide the design of new production systems that match the objectives of climate change mitigation.

The soil conservation area in Mexico City has lost, over the last 20 years, a forest vegetation area of approximately 10,000 ha (Centro GEO-PAOT 2010). In the last 50 years, forest land has changed to maize, other cereals, and cactus crops, in which plant stems (cladodes) are utilized for vegetables (cactus paddles, *nopalitos*), with high consumption in the country, plus other food and pharmaceutical uses (Sáenz-Hernandez et al. 2002). *Opuntia ficus-indica* L. Mill. is a species of the genus *Opuntia* with the highest domestication in the world (Griffith 2004), which in Mexico has resulted in intensive farming systems for fruit (prickly pear) and vegetable production (“nopalitos”). The area under study belongs to

the mountainous south region of Mexico City. The soils where the research was located show a degree of erosion between mild and moderate (Bolaños-González et al. 2016).

Opuntia production has diversified worldwide, especially as an alternative for areas of low precipitation (Ochoa and Barbera 2017). Cultivation of *Opuntia* in the mountain area of the Valley of Mexico was introduced around 1950, and gradually, its importance has been increasing in parallel to the greater consumption of nopalitos in the country and abroad. Cactus cultivation in the mountainous zone of Mexico City can be established in fields that historically are used to grow maize with low inputs (Fig. 1a) or in lands with natural vegetation (mainly *Quercus* and *Pinus*); the latter option is currently subject to restrictions due to policies to preserve the scarce forest areas that persist in the mountainous area south of Mexico City. A distinctive feature of the production system is the incorporation of composted manure mixed with crop and household vegetable residues, which is applied on the soil surface, forming mulch (Fig. 1c), which may or not be incorporated into the soil by means of a disk or chisel tool. It is widely documented in the literature that organic or plastic mulching favors lower soil transpiration rates and thus moisture conservation (Chakraborty et al. 2008). Concerning CO₂ emissions, comparisons between low-input maize (as monoculture) and cactus crop are lacking in terms of the results

Fig. 1 **a** Maize field with legume association (*Vicia faba*). **b** Cactus crop with organic mulching consisting of manure and plant residues. **c** Maize field with conventional management, Santa Ana Tlacotenco (Milpa Alta, Mexico City). Photographies by Tania Leyva Pablo

from soil respiration. The objectives of the study were (1) to compare C–CO₂ emission patterns during 1 year for maize, cactus crop, and forest systems and (2) to observe the relationship between soil respiration and soil total organic carbon (TOC) data. The six systems were two low-input maize managements (conventional tillage and maize associated with a legume, *Vicia faba*), two cactus crop systems (with and without organic mulching), soil under natural vegetation, oak-pine forest, and a 4-year soil fallow.

2 Materials and methods

2.1 Site location, climate, and soil

The area under study was selected because it presents a variety of agricultural management systems (representative of Central Mexico agro-ecosystems) that can be compared in terms of soil C–CO₂ emissions and TOC content in the soil. Maize is grown as monoculture with conventional tillage and fertilization, and it is associated with legumes, pumpkins, and other species (cornfield, *milpa*), with applications of manure generated in small production units.

The study site is localized in Santa Ana Tlacotenco, Mexico (19° 10' 44" N and 99° 00' 10" W), at an average altitude of 2595 m (CONAGUA 2015). The climate is C (w2) (w) (García 1988), tempered-humid, with summer rains, and an annual temperature and rainfall of 15.5 °C and 704.6 mm, respectively. The months with rainfall higher than 50 mm are those from May to October (Fig. 2). The soils are formed from low weathered volcanic particles (Rodríguez-Gamiño and López-Blanco 2006), dominated by sand and silt (sandy-loam textural class; Fig. 3). The main soil unit is *Phaeozem* (haplic) (INEGI 1979). According to INEGI soil mapping (1979), the three sampling sites of the management systems compared in the present study present very similar climate and soil conditions (Rodríguez-Gamiño and López-

Blanco 2006). The reaction of the soil is neutral to moderately acidic (0–30 cm deep), and in soils with natural vegetation, the organic matter content ranged between 8 and 13 g 100 g⁻¹ in a previous work (Rodríguez-Gamiño and López-Blanco 2006). Soil texture at the three sites of the current study is dominated by sand particles, with variations of clay content (amorphous) between 5 and 11 g 100 g⁻¹ (textural sandy loam class; Fig. 3).

2.2 Management systems

The selection of management systems was guided by the economic importance of the crops and the type of management. The two main crops in Milpa Alta are cactus crop (*Opuntia ficus-indica*) and maize, at a proportion of 2:1, respectively, on a harvested-area basis. The cactus crop provides additional income to small producers' family economies, while maize guarantees a portion of family food. The cactus crop continues to be interesting for family producers even though other regions of Mexico have increased the production area. A second selection criterion was the type of management system practiced in the region, one based on the incorporation of organic matter and another, conventional-type management system, based on industrial inputs. In cactus crop organic management predominates, whereas in maize, the more frequent management is conventional management (mineral fertilizers and tillage based on plow disking).

The selected management systems were the following: (1) maize monoculture with conventional tillage and fertilization (Maize_{conv}), (2) maize associated with *Vicia faba* and manure addition (Maize_{+leg}), (3, 4) cactus without and with composted manure mulching (Cactus_{-mulch}, Cactus_{+mulch}), (5) soil of pine–oak vegetation (forest), and (6) maize fields under 4 years of soil fallow and without weed control (fallow). The duration of two maize managements was 5 and 9 years for both cactus crop managements, before 2014 year, according to information provided by the cooperating producer (Mr. Arnulfo Melo). Maize plots and forest area are located on fields

Fig. 2 Monthly mean values for air temperature and rain reported since 1981 by National Meteorological Service (CONAGUA, México, 2015) (station number 9045; Santa Ana Tlacotenco, Milpa Alta, Ciudad de México). <http://smn.cna.gob.mx/es/informacion-climatologica-ver-estado?estado=df>

Fig. 3 Satellite photo (December 2015 by INEGI) and representation of three field sites (A, B, C) where CO₂ emissions and soil samples were taken. For each site is indicated the management system with its

corresponding number; the points of CO₂ soil emission measurements are indicated by circles in blue color. Distances between sites were obtained with the Google Earth® software (2017)

separated by 4 and 2.5 km from the main human settlement of Santa Ana Tlacotenco, while cactus plots are localized in the vicinity of the inhabited area (Fig. 3); one field by

management system was included in the study (Fig. 3). Some farming practices, such as the tillage method and the nature of soil fertilization inputs engaged by the owners of the

fields, were recorded by direct interviews to cooperating producer. Soil plowing in maize_{conv} was performed with disking (20 cm deep), while maize_{+leg} was plowed with a moldboard plow and animal traction (15–20 cm deep). The maize seeding was done at April 6, 2014 for both management systems. Organic additions in maize_{+leg} have been made during the last 5 years with sheep and pig manure (small-scale production in owners' households). Approximate rates of organic inputs for each management system appear in Fig. 3.

2.3 Soil C–CO₂ measurements

Measurements of CO₂ flux pulses were performed approximately every 15 days at 5 points of each plot (Fig. 4); total date measurements at each point were 22 in 1 year. The first sampling date was December 1, 2013, and the last, December 21,

2014. All measurements were performed in the morning, between 9 and 12 h; soil respiration chambers were provided with a suction pump, and a portable-meter C–CO₂ infrared analysis system (PP Systems, Hitchin, UK EGM-4) was utilized. The chamber was placed on bare soil with measurements at 30-s intervals. Flow rate units were C–CO₂ mg m⁻² h⁻¹. For forest and cactus_{+mulch} prior to each measurement, litter and mulch were withdrawn, respectively, placing the portable meter on the soil surface.

2.4 Soil water content

Volumetric soil moisture (100 cm³ cm⁻³) was measured with a TDR (time domain reflectometry) (mini-TRACE® brand) (Timlin and Pachepsky 1996; Regalado et al. 2003), with standard wave guides exploring 15 cm soil depth. Determinations

Fig. 4 Soil C–CO₂ emissions (solid lines) and soil water content (SWC, dashed lines) according to soil management system and sampling date. Standard deviation (plus sign) is marked for C–CO₂ and SWC mean values. Dates (day.month) were: 2013 year: 1 (01.12); 2 (15.12); 2014 year: 3 (26.01); 4 (09.02); 5 (23.02); 6 (16.03); 7 (06.04); 8 (20.04); 9 (09.05); 10 (01.06); 11 (15.06); 12 (30.06); 13 (13.07); 14 (26.07); 15 (07.08); 16 (21.09); 17 (07.10); 18 (19.10); 19 (02.11); 20 (18.11); 21 (07.12); 22 (21.12)

of soil moisture were performed at the same point and during the time of soil respiration determinations.

2.5 TOC content in the soil

Total organic carbon (TOC) content in the soil was quantified using the method of wet oxidation of Walkley and Black as has been previously reported (Bautista-Cruz et al. 2017).

2.6 Statistical methods

The data were processed utilizing the JMP ver. 11 statistical software program (SAS Institute 2014). Given the data distribution asymmetry of the variables measured (C–CO₂ and soil moisture), these were transformed employing the natural logarithm to achieve closer proximity to normal distribution. For statistical analysis, the six different soil-management types were considered. Measurements for each management system were replicated at 5 points (Fig. 3) and measured on 22 dates for CO₂ emissions. A linear mixed model was employed in which the response variables comprised the natural logarithm of C–CO₂ and soil moisture. An analysis of variance was performed; least square means were tabulated (Table 1). The model's fixed effects comprised management system and sampling date, while random effects included replicates and residuals. The study assumes homogeneity of the soil in terms of soil properties (INEGI 1979 reported Paheocem haplic in all three sites). When significant effects on the model existed, the management system means were compared with Tukey test ($P < 0.05$). Linear regression analysis was performed to estimate the degree of association between soil moisture and CO₂ emissions. To describe the evolution of C–CO₂ and soil moisture rates along the 22 dates, averages and standard deviations (SD) of the untransformed values were plotted. The coefficient of variation (CV) was calculated for C–CO₂ flux emissions.

Table 1 C–CO₂ emissions (mg m⁻² h⁻¹) and soil water content (cm³ cm⁻³) (least squares mean values) (a) for 22 dates, and (b) for 13 dates corresponding to maize growth period and total organic carbon (g 100 g⁻¹). Letters in vertical sense correspond to mean groups ($P < 0.05$). For C–CO₂ emissions and soil water content, the standard

Management	C–CO ₂ flux (mg m ⁻² h ⁻¹)		Soil water content (cm ³ 100 cm ⁻³)		TOC (g 100 g ⁻¹) (mean ± SD)
	All dates	Maize period	All dates	Maize period	
Maize (conv)	177 (bc)	218 (a)	8.8 (abc)	11.0 (a)	2.05 ± 0.50 (gd)
Maize (leg)	169 (c)	205 (a)	9.2 (ab)	11.0 (a)	2.87 ± 1.39 (d)
Cactus (no-mulch)	227 (ab)	178 (a)	7.5 (d)	9.9 (a)	5.93 ± 2.00 (ab)
Cactus (+ mulch)	201 (abc)	172 (a)	9.4 (a)	11.8 (a)	4.82 ± 1.38 (abc)
Forest	243 (a)	268 (a)	8.0 (bcd)	10.8 (a)	6.38 ± 0.74 (a)
Fallow	203 (abc)	215 (a)	7.8 (cd)	10.3 (a)	3.78 ± 1.15 (bcd)

3 Results and discussion

3.1 C–CO₂ fluxes for each management system

Soil respiration curves for each management system presented particular patterns. Soils with maize exhibited peaks of > 1000 mg C–CO₂ m⁻² h⁻¹ during rainy months, while during months prior to sowing in which maize plants had not been established (December 2013 to March 2014), low values of soil respiration were recorded (Fig. 4a, b), due to the reduction of autotrophic respiration and the possible effect of low temperatures on microbial activity (Schmidt et al. 2011). While variable, autotrophic respiration may represent 50% of soil respiration in the case of forests (Högberg et al. 2009) and becomes even greater for crops (Hanson et al. 2000), in the case of maize (conventional), as the rainy period advanced, a trend of increased respiration was observed with peaks on June and September (Fig. 4a). The highest values of soil respiration under maize (conventional) occurred during the rainy season (Fig. 4a), which had in 2014 higher rains in spring-summer period than the historical average (Fig. 2). Maize_{+leg} showed a trend similar to that of conventional maize (Fig. 4b; Table 1) with slightly lower average values of respiration, although the differences were not significant (Table 1). During the months with low temperatures, respiration peaks were not observed for any of the management systems (Fig. 4). It has been noted that within the goal of reducing greenhouse gas emissions, these soil respiration peaks should be reduced in agro-ecosystems (Moyano et al. 2013). In the present study, these peaks were less frequent and less pronounced in cactus crops as compared with maize systems (Fig. 4c, d); it is likely that practices such as fertilizer application during the rainy period may exert an influence on the increased flow of C–CO₂ (Stockmann et al. 2013).

The two cactus managements demonstrated soil respiration values between 50 and 400 mg C–CO₂ m⁻² h⁻¹ during the

errors were 1.16 and 1.09, respectively (all dates), and 1.13 and 1.05 (maize period). TOC mean data correspond to that reported by Bautista-Cruz et al. (2017); data re-use license (number 42388511741) by Land Degradation and Development journal (John Wiley and Sons), November 30, 2017

rainless period (December to April; Fig. 4c, d). This result is consistent with the perennial character of cactus, whose roots and associated microflora remain active even at low seasonal temperatures and residual moisture (Snyman 2006). Cactus_{mulch} presented a single respiration peak on June 15 (Fig. 4c), which coincides with high moisture in the soil, and could be explained by an increased concentration of organic substrates in soil and increased microbial activity (Moyano et al. 2013). At September 21 (rainy season), the two cactus managements presented soil respiration values lower of those recorded for maize (Fig. 4).

The two maize systems showed highest values of coefficient of variability (CV) of the C–CO₂ flow (126.5 and 95.8 for maize_{+leg} and maize_{conv}, respectively). The system with lowest variability of CO₂ emissions was the natural vegetation of oak-pine (forest), followed by soil fallow (Fig. 4f) and cactus_{+mulch}, with CV of 52.7, 74.7, and 76.3, respectively. In these three management systems, soil respiration peaks were not found, which is suitable for the purpose of reduction of C–CO₂ emissions from soil respiration (Moyano et al. 2013). However, in a study comparing soil respiration rates in the Cofre de Perote volcano region (Mexico; Campos 2006) at an altitude between 1450 and 1530 m, the variability of soil respiration rates was lower than those reported here although the soil respiration was assessed using a different method; grassland management and corn–potato–maize rotation had lower CV than those reported for cloud forest (Campos 2006).

3.2 Comparison of mean values of C–CO₂ fluxes among management systems

Average CO₂ emissions on the 22 sampling dates for the management systems were significantly different ($P < 0.5$; Table 1). Oak-pine forest exhibited the highest C–CO₂ flow rate, followed by cactus crop; it is noteworthy that in both cactus and forest soil environments, active root systems are maintained throughout the year, with their autotrophic respiration. However, in the maize system, its roots remain for only 8 months. C–CO₂ mean values for the two maize managements were similar and were below those of the remaining four management systems, due to the absence of plants during the first 3 months of the year and during plant senescence at the end of the farming cycle during the months of November and December. Soil on fallow presented soil respiration values similar to those of cactus_{+mulch}; in this system, weeds grew without any control, which may explain the relatively high soil respiration in this case.

Considering CO₂ emissions for 1 year, average respiration in maize crop was significantly lower than the rest of the treatments. In a previous work conducted in the Cofre of Perote volcano region (Mexico), soil respiration values were ordered as follows: grassland > corn–potato–corn > tropical cloud forest (Campos 2006). When the soil respiration

averages for all management systems were calculated, including only the growing maize period between April 20 (seeding) and November 18, 2014 (harvest), no significant differences were found between management systems (Table 1).

The lower respiration rate in maize fields compared to that in forest can be related, on the one hand, to the 4 months during which the soil is without growing plants and, on the other, to a decrease in soluble carbon (Schmidt et al. 2011) due to the low levels of organic carbon (Table 1) that these fields accumulated over at least five past decades.

3.3 Relationship between soil moisture and soil respiration

The regression analysis conducted with soil water content data and the C–CO₂ of each management system showed some significant correlation coefficients for conventional and legume association maize managements ($R^2 = 0.11$ and 0.05 ; $P < 0.001$ and $P < 0.05$ respectively) and forest with natural vegetation ($R^2 = 0.06$, $P < 0.01$) with positive associations between both variables. This type of response is consistent with that reported in the literature (Moyano et al. 2013). However, the degree of association between soil moisture and respiration is weak, judging by the low values, which suggests the involvement of other variables not measured in the study with an effect on respiration levels, such as soil temperature (Campos 2006) and other ecosystem and biological variables (Schmidt et al. 2011).

The two managements of cactus crop demonstrated only a slight trend (not statistically significant), in which the increase in soil moisture resulted in a decrease in C–CO₂ emissions. This trend is consistent with the average soil respiration values exhibited by cactus crop during the rainy season (April to October; Fig. 2), which were lower compared with those of the average annual cycle of the 22 measurements (Table 1). It may be hypothesized that this behavior of soil respiration under cactus can be associated with Crassulacean acid metabolism (CAM) plants (to which *Opuntia* genus belongs) well adapted to water-stress conditions. The literature reports that during the rainy season, species with CAM metabolism, particularly *Opuntia ficus-indica*, respond with rapid growth of new roots (rain roots; Snyman 2006), and this process is carried out with high efficiency with low respiratory cost, allocating the largest part of C photosynthates to new root-tissue structures (Nobel et al. 1992). These root growth patterns may be associated with low C–CO₂ emissions due to autotrophic respiration.

3.4 Total organic carbon content in the soil

Highest TOC content was detected in forest soil and represents the upper limit of the plots under study ($6.3 \text{ g } 100 \text{ g}^{-1}$), while the two cactus treatments were slightly lower (no

significant differences; Table 1). This high carbon (C) content in the soil of the two cactus crop treatments can comprise an additive effect of the contributions originated by the cactus plant roots and the occasional incorporation of mulching during the 35 years of continuous cultivation under both management systems. For both maize systems, the contents of TOC in soil were similar and corresponded to the lowest values of the six management systems, although the system receiving manure additions demonstrated a slightly higher value of TOC (no significant; Table 1) compared with the monoculture system. Maize_{+leg}, considering all the year, showed a tendency to reduce C–CO₂ emission value (Table 1); thus, this management system could be more appropriate for use in a strategy for reducing C–CO₂ emissions and TOC conservation in soil as compared with the maize monoculture system. Systems with low organic inputs and low fertilization such as maize_{conv} produce low biological and economic yields, which leads to diminished incorporation of plant residues into the soil, thus rendering these prone to decay in the stock of TOC in soil (Janzen 2006). Moreover, it has been shown that simultaneous root systems with different architectures (maize, common bean, and pumpkin) represent benefits in terms of increases in root biomass in soil profile and nutrients absorption (Zhang et al. 2014).

Plots under the two cactus crop systems had higher TOC compared with plots with maize monoculture, confirming that the perennial cactus crop contributes to TOC storage at a similar level to that of soil under forest (Bautista-Cruz et al. 2017). Cactus functions as a carbon sink under management conditions practiced in the area, while TOC data for maize moved within the range of 2.0–2.9 g 100 g⁻¹, indicating a 50% decline in TOC content reached in forest soil. TOC decline is typical in lands aged between 30 and 50 years or more under low-intensity agriculture (Post and Kwon 2000). According to information provided by the local land authority (M. Amulfo Melo Rosas), maize plots at site C were cultivated with maize prior to the 1932 Mexican agrarian distribution; thus, plots are likely to be more than 100 years old in the production of maize or other cereals, while cactus production (site A) began in the 1980s, resulting in approximately 35–40 years of cactus cultivation.

The contributions of manure generated in the same locality mean savings in transport costs and less environmental impact compared with manure carried from the intensive dairy area located > 50 km from the local production area. However, due to the small scale of livestock production in family units of the region under study, local contributions of manure would not be sufficient to maintain TOC in soil cultivated with maize.

Perennial plants maintain roots at greater depths with respect to annual crops; therefore, soil respiration occurs throughout the year (Davidson et al. 1998), as reported in the current study for forest and the two cactus managements. The pattern of stable respiration throughout the year for the

forest with natural vegetation must consider, besides the role of roots of living plants throughout the year, the activity of a diverse and complex microflora (bacteria, and saprophytic and mycorrhizal fungi) in the soil of forest under natural vegetation in relation to the agricultural fields, as well as an increased abundance of carbon sources in soil (Metcalfé et al. 2011). Concerning the high TOC levels in soil under cactus can be explained by the system of roots of these plants, which allows for high efficiency in water use in arid and semi-arid areas (Snyman 2006). In addition of tap and lateral roots, cactus produces roots that grow rapidly and that remain alive for only a few days after the rains (Snyman 2006). These rain roots die quickly (within a period of several days) and are incorporated into the process of decomposition of organic matter in the soil. In a semi-arid region of Brazil, (Dubeux-Junior et al. 2013) found that *Opuntia-ficus indica* produced 136 g of roots per plant at a density of 20,000 plants ha⁻¹, a density very similar to that of the current study. Considering an approximate proportion of 0.4 C in root biomass (De León et al. 2006), an estimate value of C provided by cactus crop plants to the soil would be 1 t ha⁻¹ (on dry basis) with the plant density cited previously. The growth dynamics of different types of cactus roots (coarse and fine) throughout the year and their relationship with changes in soil moisture, as well as the specific contribution to the soil carbon, are knowledge gaps that require new investigation.

In terms of management systems, it is desirable to restrict the use of forest conversion to agricultural use due to the environmental services that the forest provides in the water and carbon cycles. For land already under agricultural use, the cactus crop is presently contributing effectively to the accumulation of organic carbon in the soil; thus, this crop must be considered a management option for forest soils that changed to agricultural use. Concerning maize cultivation represents lowest values of TOC in the soil; therefore, the inclusion of legume plants should be raised that favor the fixation of atmospheric nitrogen and that could improve TOC accumulation in the soil, as occurs in the traditional cornfield (*milpa*) (Zhang et al. 2014). The results of this study indicate that another possibility comprises inserting rows of cactus crop between rows with maize, which has not been tested to date, to our knowledge, in Central Mexico or in another region of the world.

4 Conclusions

The conventional maize system presented the highest peaks of soil respiration, while the cactus crop showed a more stable pattern, similar to that of the oak-pine natural vegetation. The fall of TOC in soils cultivated with low input maize monoculture can be reversed with cactus cultivation.

It is recommended, for the ecological area of Mexico City and other regions, to analyze the combination of perennial species (mainly cactus crop but also other orchard plant species) with maize production, so that the objectives of feeding the family unit can be combined with the ecological advantages of perennial crops in relation to the conservation of organic carbon in the soil.

Acknowledgements The authors also acknowledge the technical field support for the measurement campaign (2013–2014) by Gabriela Miranda Garcia, as well as the facilities and historic land use provided by the local producer Mr. Arnulfo Melo Rosas, president of the Ejido of Santa Ana Tlacotenco.

Funding information The authors acknowledge financial support from the Instituto Politécnico Nacional (IPN) for funding (2012–2015) the joint project CIIDIR-UAMX *Biological properties and CO₂ emissions in rhizospheres of different soil management systems in the Conservation Soil in Mexico City*. The National Council of Science and Technology (CONACYT, Mexico) financed the Master in Science program of Tania Leyva-Pablo.

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