Evolution of soil organic carbon during a chronosequence of transformation from cacao (*Theobroma cacao* L.) plantation to grassland

Evolución del contenido de carbono orgánico del suelo en una cronosecuencia de reemplazo de plantación de cacao (*Theobroma cacao* L.) a pastizal

Pedro Salvador Morales[1,6], Rufo Sánchez Hernández[2*], Delfino Sánchez Gómez [1], Ulises López Noverola[2], Gelacio Alejo Santiago[3], Eduardo Valdés Velarde[4] and Juan Fernando Gallardo Lancho[5]

[1]Instituto Tecnológico de la Zona Olmeca-ITZO, México. [2]División Académica de Ciencias Agropecuarias, UJAT, Carretera Villahermosa-Teapa km 25 R/A. La Huasteca, Segunda Sección Villahermosa, Tabasco, México. [3]Unidad Académica de Agricultura, Universidad Autónoma de Nayarit, México. [4]Departamento de Fitotecnia, Universidad Autónoma Chapingo, Texcoco- México. [5]C.S.I.C., Instituto de Recursos Naturales y Agrobiología de Salamanca, España. [6]División Académica de Ciencias Biológicas, UJAT, México. Author for correspondence: *rusaher@hotmail.com*

Abstract

The aim of this research was to evaluate the impact of the soil use change of the Cocoa Agroforestry System (CAS) on soil organic carbon (SOC) levels and other indicating soil chemical fertility properties (edaphic density ρ_b, cation exchange capacity CEC, soil total nitrogen STN), when a soil use change occurs from CAS to grassland (GL). For this, in order to be selected was recorded, considering different time intervals (1-5, 6-10 y 11-20 years). However, a CAS of 20-35 years was considered as a reference. In addition, soil samples were taken at -30 cm depth to determine the contents of SOC, STN, CEC, ρb, soil organic matter (SOM) and the soil C/N ratio. Consequently, the soil penetration resistance was evaluated *in situ*. The results indicated the change in soil use from CAS to GL, did not cause a significant decrease in the amount of stored SOC (0-30 cm) during the considered time with respect to CAS. However, if only the first -10 cm of soil is sampled, a significant soil compaction is observed throughout a decrease in the CEC value in the long term (20 years).

Key words: Soil use change, edaphic apparent density, soil fertility, soil organic matter, edaphic C/N relationship.

Resumen

El objetivo de esta investigación fue evaluar el impacto del cambio de uso de suelo del Sistema Agroforestal de Cacao (SAFC) sobre los niveles de Carbono Orgánico del Suelo (COS) y otras propiedades indicadoras de la fertilidad edáfica (densidad aparente ρ_b, capacidad de intercambio catiónico CIC, N total del suelo NTS), cuando se produce un cambio de uso de suelo de SAFC a pastizal (PZ). Para ello, se seleccionaron sitios donde se registró este cambio de uso del suelo, considerando diferentes intervalos de tiempo (1-5, 6-10 y 11-20 años). Como referencia se consideró un SAFC de 20-35 años. Adicionalmente, se tomaron muestras de suelo a -30 cm de profundidad para determinar los contenidos de COS, NTS, CIC, ρ_b, materia orgánica del suelo (MOS) y la relación C/N edáfica. Consecuentemente, se evaluó la resistencia a la penetración del suelo *in situ*. Los resultados indicaron que el cambio de uso de suelo SAFC a PZ, no ocasionó una disminución significativa de la cantidad de COS almacenado (0-30 cm) durante el tiempo considerado respecto al SAFC. Sin embargo, si sólo se muestrean los -10 cm primeros del suelo, se observa una significativa compactación edáfica, junto con una caída del valor de la CIC a largo plazo (20 años).

Palabras clave: Cambio de uso de suelo, densidad aparente edáfica, fertilidad del suelo, materia orgánica del suelo, relación C/N edáfica.

Introduction

The Cocoa Agroforestry System (CAS) is one of the most important, which are distributed in the states of Tabasco and Chiapas (South of Mexico). However, in recent times, this system is facing phytosanitary problems, coupled with low yields due to inadequate crop management (Bautista-Mora *et al.,* 2016), which is causing that currently is cutting plantations in favor to other crops. In accordance with Don *et al.* (2011), the soil use change is the second most important source of variation that man has caused to induce CO_2 emissions. In particular, deforestation in the tropics and subtropics causes loss of biomass and soil organic carbon (SOC). The soil use change can affect SOC levels due to the variation of production, which can reach to the soil and by acceleration in the decomposition rate of organic wastes (OW). Therefore, factors such as crop management, some species are being incorporated, as well as the OW characteristics, affect the SOC storage capacity (Jandl *et al.,* 2007). According to Schroth *et al.* (2015), CAS can accumulate a significant amount of tree biomass (which means: storage of soil organic carbon in high amounts, sometimes even higher than some natural forests).

Other important aspects which are modified by the reduction of the soil organic matter (SOM) content, are the contents of soil total nitrogen (STN) and assimilable forms of soil nutrients.

According to Yoneyama *et al.* (2015), for the nutrients supply to the higher plants, which requires abundance of OW, since they are sources of SOM. After the humification process, in which a microbial activity intervenes (after the crushing caused by soil mesofauna), being responsible for the release of nutrients, which can be absorbed by plant roots, aided by the hyphae of mycorrhizal fungi. In Tabasco-México, the largest surface area of CAS is distributed in the region of the Chontalpa, an area where the grassland system has recently registered a significant increase in its surface area (Ramos, Sánchez & Gama, 2016). However, modifications in physical, physicochemical and biochemical properties have not been sufficiently evaluated (in particular, SOC storage), which are being triggered by this change in soil use. Given these concerns, the aim of this research was to evaluate the modification of SOC levels and other edaphic variables (edaphic density, penetration resistance, cation exchange capacity (CEC), STN and C/N ratio), which are indicative of edaphic fertility in a chronosequence of established pastures after cacao plantations felling.

Material and methods

Study area

The research was carried out in the communities Iquinuapa, Hermenegildo Galeana and Soyataco belonging to the municipality of Jalpa de Méndez, Tabasco-Mexico, places that are located within the geographical coordinates 10° 33´ N and 93° 45´ W (Figure 1).
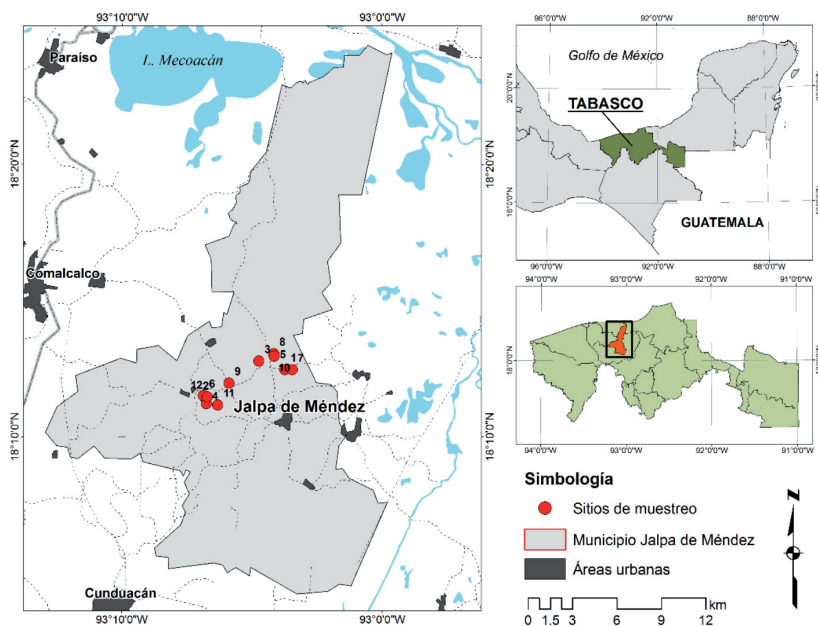

Figure 1. Location of sampling sites in communities of Jalpa de Méndez, Tabasco-México.
Source: INEGI (2006).

Weather conditions

The climate corresponds to a warm-wet, with abundant rains in summer. The average annual temperature ranges between 24 and 28°C and the average annual rainfall between 1500 and 3000 mm.year^{-1} (INEGI, 2006).

Geological components

The dominant geological materials are deep sediments, which were carried by numerous rivers and streams that cross the zone from the weathering of the Sierra rocks and the soil hills erosion, mainly during the recent Quaternary period. These materials, which are composed of different mineral mixtures, were finally deposited by a continuous avenues, constituting currently a great land extensions (Palma *et al.,* 2007).

Soil types

The soils were formed from such Quaternary sediments, they are young soils, in any case from Holocene period (Palma *et al.,* 2007). According to the soil map provided by: Jiménez *et al.* (2013), predominate the Gleysols soils.

Plant cover

According to Palma *et al.* (2007), the native vegetation of this area corresponds to a medium-evergreen forest. However, this type of vegetation has been replaced by a native and improved grasslands, where are still conserved the Cocoa Agroforestry System (CAS), which have a great diversity of flora, highlighting approximately 28 families, 58 genera and 67 species (Sánchez-Gutiérrez *et al.,* 2016), among them being the most important: *Erythrina americana* Mill., *Erythrina poeppigiana* (Walp.) O.F.Cook, *Gliricidia sepium* (Jacq.) Walp. (Fabaceae), *Cedrela odorata* L. (Meliaceae) and *Colubrina arborescens* (Mill.) Sarg. (Rhamnaceae).

Soil samples

Sites which were formerly CAS were selected, due they underwent a change in soil use. In order to select the sampling sites in a first stage, a survey was carried out with the producers in order to know their crop management record, in particular the number of years since the change of soil use. From the survey results, was determined the major change of soil use, which was from CAS to grassland (GL). The years of soil use change, which were reported by farmers, were organized into a database, establishing soil use ranges as follows: 1-5 years (GL$_5$), 6-10 years (GL$_{10}$) and 11-20 years (GL$_{20}$). Each time interval was considered as treatment, with four plots (replicates) for each treatment. As reference treatment (control), CAS plots of 20-35 years of establishment (CAS$_{35}$) were sampled, where each plot was considered as an experimental unit.

Determination of soil physical properties

A first soil sample set was taken with a cylindrical sampler of known volume for the edaphic density determination. In each experimental unit, 10 sampling sites were located. Alternatively, at each soil sampling site, soil samples were taken at three depths as follows: 0-10, 10-20 and 20-30 cm, respectively. Soil samples were dried in a forced air oven at 105°C until constant weight. The dry weight of soil sample was related to the volume of the cylinder for to calculate the edaphic density (ρ_b). In addition, the penetration resistance was measured *in situ* with a Bush SP1000 ELE penetrometer fitted with a force sensor and a displacement sensor. Conversely, a standard cone was used (*ASAE,* 30°) with a diameter at the base of 1.28 cm. The approximate insertion velocity was 5.0 cm. s^{-1} and the penetration resistance was expressed in MPa.

Determination of soil biochemical properties

Another research stage, consisted in obtaining composite soil samples (from 10 subsamples per experimental unit) taken at -30 cm soil depth. These samples were dried in the shade, crushed in plastic trays and then sieved to obtain a particle size of less than 2.0 mm. In addition, these samples were determined SOM by the Walkley & Black method, STN by Kjeldahl semi-micro method and CEC by the ammonium acetate extraction method, processes that allows to generate a subsequent quantification by atomic absorption, respectively. The SOM percentage was calculated using 1.72 factor from SOC value. In fact, ρ_b was used to transform the SOC results obtained as Mg of C. g^{-1} to values of Mg of C. ha^{-1}.

Data analysis

The collected data were analysed using the GLM procedure from Statistical Analysis Systems (SAS, 2002) for Windows, version 6.12 ®. To identify significant difference among treatments and statistical significance for all comparisons was made at $p<0.05$. Tukey's multiple range test was used to compare the mean values of treatments.

Results

Soil physical properties

In the edaphic density (ρ_b) variable, statistical differences were observed for each treatment factor and soil depth factor (Table 1). In the soil surface

horizon (0-10cm), the treatment GL_{20} performed the highest significantly value ρ_b, being of 1.3 Mg. m^{-3} (Table 1). In fact, the lowest value with GL_5 and GL_{10}, which were statistically equal to CAS_{35} (1.00 Mg. m^{-3}).

It was observed that in Table 1, in general, as the soil depth sampling increases, the ρ_b value increases in each treatment. It is known that, is due to the fact in the first soil surface horizon (0-10 cm) a higher SOM content accumulates, which decreases with respect to soil depth, the effect on soil structure (and, therefore, the soil porosity), decreases significantly. Therefore, as the soil depth sampling increases, a significant increase in ρ_b in each treatment can be observed. (Table 1), which were inversely correlative to the SOM concentration.

Table 1. Edaphic density (ρ_b) values and soil compaction (0-30 cm) with different soil uses (grassland (GL) and Cocoa Agroforestry System (CAS)) in the Southeast of Mexico

Treatment	ρ_b (Mg. m^{-3})			Soil compaction (MPa)			SOM
	Soil depth (cm)			Soil depth (cm)			(%)
	0-10	10-20	20-30	0-10	10-20	20-30	0-30
GL_5	1.1 ±0.16a	1.3 ±0.10	1.4 ±0.19	4.4 ±1.1a	3.9 ±0.1a	4.2 ±0.9a	2.5 ±0.85a
GL_{10}	1.0 ±0.40a	1.1 ±0.11	1.3 ±0.21	4.7 ±1.1a	4.9 ±1.0a	4.3 ±0.5a	3.5 ±0.75a
GL_{20}	1.3 ±0.13b	1.3 ±0.14	1.4 ±0.16	4.4 ±1.0a	4.7 ±0.6a	4.2 ±0.7a	2.5 ±1.6a
CAS_{35}	1.0 ±0.03a	1.2 ±0.05	1.3 ±0.10	3.5 ±0.5a	4.7 ±0.8a	4.5 ±0.5a	2.8 ±1.9a
Mean	1.1 ±0.40a	1.2 ±0.14b	1.3 ±0.21c	4.3 ±0.9	4.6 ±0.8	4.3 ±0.7	2.8 ±1.3

§ Different letters indicate statistically significant differences (P <0.05).GL: Grassland; CAS: Cacao agroforestry system; SOM: Soil organic matter.

There were no statistically significant differences in relation to soil compaction values in the soil surface horizon, both for treatment factor and soil depth factor (Table 1).

Soil physical-chemistry properties

In relation to soil CEC, it was significantly higher in CAS_{35}, GL_5 and GL_{10}, which were statistically equal to each other (27, 27 y 23.7 $Cmol^{(+)}.kg^{-1}$, respectively). A significantly lower value of CEC, was obtained in the longest grassland (GL_{20}; Table 2) being between 15 and 20 Mg. g^{-1} for SOC and 1.5 to 1.6 Mg. g^{-1} for STN.

Soil biochemistry properties

There were no statistical differences in the contents of SOC and STN among different treatments (Table 2).

The C/N ratio in CAS is also significantly similar to the grassland systems (GL) (Table 2), a consequence of high soil spatial variation. Regarding the vertical distribution by treatment of SOC, in fact, was significantly higher in soil depth of 0-10 cm for the following treatments: GL_{10}, CAS_{35} and GL_5 (3.3 mg of C. g^{-1}), respectively, among which there was no statistical difference (Table 3). The GL_{20} treatment

performed the lowest SOC percentages (being 21 mg of C. g^{-1}). For soil depth of 10-20 cm and 20-30 cm, the SOC did not present significant difference for each treatment (Table 3), being in any case, significantly lowest to those for edaphic surface horizon.

Table 2. SOC contents and some edaphic chemical properties (0-30 cm) of a chronosequence from grassland (GL) to CAS in the Southeast of Mexico

Treatment	SOC	STN	CEC	C/N
	(Mg. g^{-1})		($cmol^{(+)}. kg^{-1}$)	
GL_{1-5}	15 ±5.3a	1.5 ±0.3a	23.7 ±0.5ab§	10 ±5.2a
GL_{6-10}	20 ±4.6a	1.6 ±0.1a	27 ±4.1a	13 ±3.5a
GL_{11-20}	15 ±9.5a	1.5 ±0.4a	21 ±3.3b	10 ±3.6a
CAS_{20-35}	17 ±10a	1.6 ±0.1a	27 ±3.2a	10 ±6.0a
CV	36.3±7.3	12.6±0.2	11.9±2.8	24.2±4.6
mean > F	0.18	0.59	0.05	0.72

§ Different letters indicate statistically significant differences (P <0.05).GL: Grassland; CAS: Cacao agroforestry system; SOC: Soil organic carbon.

Table 3. SOC Vertical distribution in a chronosequence of grassland to CAS in the Southeast of Mexico (determined by edaphic layers).

Treatment	SOC (%)			SOC
	Soil depth (cm)			(Mg C.ha^{-1})
	0-10	10-20	20-30	
GL_{1-5}	2.3 ±0.15ab§	1.3 ±0.65a	0.8 ±0.57a	46.8 ±7.1b
GL_{6-10}	3.6 ±0.90a	1.5 ±0.34a	1.1 ±0.70a	82.4 ±9.0a
GL_{11-20}	2.1 ±0.78b	1.6 ±0.55a	0.9 ±0.35a	63.4 ±8.9ab
CAS_{20-35}	3.3 ±0.28ab	1.0 ±0.10a	0.7 ±0.10a	34.7 ±3.1b

§ Different letters indicate statistically significant differences (P <0.05). SOC: Soil organic carbon. GL: Grassland; CAS: Cacao agroforestry system.

Discussion

Soil physical Properties

It is important to note that a ρ_b increase by the continuous cattle overgrazing is common in the evaluated grasslands, in fact is correlated to soil compression in the surface soil horizon, reducing the porous space and a ρ_b increased, which is what is observed in GL_{20}. In addition, SOM content is significantly the same, likely a result which cannot be attributed to its quantity, which promotes less soil aggregation. In this sense, a change in soil humic quality is not detectable since no significant variation in the soil C/N ratio is observed (Table 2). Nascente, Yuncong & Costa (2015), found that SOM concentration was negatively correlated with ρb in the surface soil horizon (0-10 cm), which are thought to contribute to a higher concentration of SOM with a lower ρ_b.

As a result, it has long been thought that a high soil compaction and high ρ_b affects negatively the agroforestry system productivity, since both conditions have allowed an adequate root plant penetration. It was observed that plant nutrition becomes difficult, due to internal air flows, water

and heat, which are limited before the porous space decreasing.

Soil physicochemical properties

A significantly lower value of CEC seems to indicate a loss of edaphic quality after 20 years of soil use change (from the grassland (GL) to cacao agroforestry system (CAS)), and provides more accurate and reliable estimates of the C/N ratio values, which were not modified with soil use change.

Liang *et al.* (2005), indicated that regardless of the SOC amount, the organic waste decomposition rate regulates many biogeochemical processes, specifically the nutrient cycles and retention. In addition, these organic wastes are mostly degraded, increasing the aromatic compounds (humification), which can be adsorbed on the clay minerals surface, which causes a greater specific soil surface area, being reflected in a greatest CEC, as it should have happened in the CAS of the present research. In fact, this clay-humic complex goodness of the agroforestry system is evident a deterioration with cattle overgrazing, since both the edaphic apparent density (ρ_b) and CEC, deteriorate in a medium term (GL_{20}).

For instance, the regression coefficient between SOM and CEC variables was 0.65 ($r = 0.02$), indicating no significant correlation (Table 1), which indicates the C/N ratio have not allowed to detect the soil use change in terms of the SOM content, is believed to be an outcome of enzymatic activities.

Soil biochemistry properties

Physical and chemical properties evolve favorably on the edaphic surface (e.g. 0-20 cm). CAS may maintain significant amounts of SOC in a reasonable time (e.g. six years) of establishment. Thereafter, the edaphic properties tend to stabilize at similar levels to secondary forests in their natural state (Arévalo-Gardini *et al.,* 2015).

It is known that high coefficient of variation (CV) of the results prevents significant differences in these properties from being observed in the present study, indicating more sensitive parameters, such as enzymatic activities, since the soil use change after CAS deforestation, which implies a bare soil. Therefore, there must be an obligatory temperature and humidity regime modification in CAS, which modifies the mineralization speed of the organic wastes (litter or mulch) provided by the CAS tree vegetation for several years.

Aceñolaza & Gallardo (1999), found that thinning of the montane alder forest of the Argentine Yunga, increased the soil dryness, which moderated the organic wastes decomposition,

while the canopy development was accelerated. During the first years of the soil use change, there may be a greater nutrient release as a result of an increased mineralization.

In fact, in a previous work, a chronosequence of grassland from 3 to 56 years of age, was evaluated. Their results indicated that 15 year old grasslands had a higher amount of C and N due to the age, the grassland system accumulated more SOM, coming specifically from plant and root organic wastes, which generated a higher SOC contribution and other nutrient uptake. After that age, there was a decrease in the release of chemical elements in such systems (Cheng & Shao (2015); Jie, Cheng, Li & Liu (2012); Tadakatsu, Ohkura & Matsumoto (2015)). Alternatively, Huang *et al.* (2010), mentioned that over the years, grasslands lose their vocation to accumulate SOC due to a decrease in the system productivity, mainly due to an increasing degradation of its properties, motivated by cattle overgrazing and the type of grassland established. Accordingly to Goodrick *et al.* (2015), some tropical agroforestry systems slowly reduce the SOC content due to the higher N contents that legumes procure (which speeds up the mineralization processes). In addition, a higher STN concentration and higher mineralization, reduces the C/N ratio, resulting in a greater SOM decomposition. Other research has documented that under certain conditions, by switching from crop to grassland, an increase in SOC levels, which can be achieved by 26% (Don *et al.,* 2011). On the other hand, Johnson *et al.* (2007), conducted a study in which they revealed the SOC amount, which can be stored in the soil as a function of the organic wastes amount produced and entering into the soil, for instance, soil composition and soil decomposition rate, noting that roots of the grasses decomposition have allowed a great amount of recalcitrant compounds.

The results found for the three first edaphic layers studied (Table 3). These results are comparable in variability to the report by Céspedes *et al.* (2012), who indicated the highest SOC content in prairies and grassland is concentrated in the first -10 cm, concentrating from 41 to 62% of the SOC (referred to SOC found at -1.0 m soil depth) in the first -20 cm. In this sense, Wei *et al.* (2012), compared the SOC content of grassland systems and secondary vegetation. Alternatively, the results indicate that grassland after 20 years of establishment can accumulate more than twice the amount of SOC than soils with secondary vegetation over 50 years of age. In addition, they indicated in the grasslands more than 50% of SOM, which was located in the first -20 cm, whereas in the secondary succession it was only 23-31% of the SOM (for that same soil depth).

However, in the present study (under conditions of the humid tropics) after 20 years of soil use change (GL_{20}) of CAS, the SOC in the 0-10 cm soil layer decreased, indicating the humification of the organic wastes did not compensate for the loss of SOM mineralization, which negatively affects the soil structure (increase of ρb) and porosity.

Conclusion

The soil use change from CAS to grassland does not significantly reduce the SOC stores (referred to 0-30 cm soil depth) in a significant way, have achieved the soil C/N ratio. In fact, a high soil spatial variation obliges us to look for other more sensitive indexes to measure the possible impact. Given these concerns, it is possible to observe a negative modification which affects the edaphic density at medium term CEC (20 years) in the first -10 cm soil depth, parallel to a significant fall of the SOC to that same soil depth, which ends up negatively affecting the soil fertility.

References

Aceñolaza, P.G. & Gallardo, J.F. (1999). Leaf decomposition and nutrient release in montane forests of Northwestern Argentina. *J Trop For Sci*, 11(3), 619-630. *http://www.jstor.org/stable/43582571.*

Arévalo-Gardini, E., Canto, M., Alegre, J., Loli, O., Julca, A. & Baligar, V. (2015). Changes in soil physical and chemical properties in long term improved natural and traditional agroforestry management systems of cacao genotypes in Peruvian Amazon. *PloSOne*, 10(7), e0136784. *https://doi.org/10.1371/journal.pone.0136784*

Bautista-Mora E., Pérez-Flores, J., Ruiz-Rosado, O. & Valdéz-Balero A. (2016). Uso de recursos forestales maderables y no maderables del Sistema agroforestal. Agroproductividad, 9(2) ,50-55.

Céspedes, F.F., Gobbi, J.A. & Bernardis, A.C. (2012). Reservorio de carbono en suelo y raíces de un pastizal y una pradera bajo pastoreo. *Rev Fitotec Mex,* 35(1), 79-86.

Cheng, M. & Shao, S. A. (2015). Responses of soil nitrogen, phosphorous and organic matter to vegetation succession on the Loess Plateau of China. *J Arid Land*, 7(2), 216–223. *https://doi.org/10.1007/s40333-014-0043-3*

Don, A., Schumacher, J. & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks: a meta-analysis. *Global Change Biol,* 17(4), 1658-1670. *https://doi.org/10.1111/j.1365-2486.2010.02336.x*

Goodrick, I., Nelson, P.N., Banabas, M., Wurster, C.M. & Bird, M.I. (2015). Soil carbon balance following conversion of grassland to oil palm. *GCB Bioenergy,* 7(2), 263-272, *https://doi.org/*10.1111/gcbb.12138

Huang, Y, Sun, W. J., Zhang, W. & Yu, Y. (2010). Changes in soil organic carbon of terrestrial ecosystems in China: A mini-review. *Sci China Life Sci*, 2010, 53(7), 766-775. *https://doi.org/10.1007/s11427-010-4022-4*

INEGI. (2006). Síntesis geográfica y anexo cartográfico del estado de tabasco. Instituto Nacional de Estadísticas, Geografía e Informática. Aguascalientes, México. *http://www3.inegi.org.mx/sistemas/productos.*

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz R., Hagedorn, F., Johnson, D.W., Minkkinen, K. & Byrne, K.A. (2007). How strongly can forest management influence soil carbon sequestration? Geoderma, 137(3-4), 253-268. *https://doi.org/10.1016/j.geoderma.2006.09.003*

Jie, W., Cheng, J., Li, W. & Liu W. (2012) Comparing the effect of naturally restored forest and grassland on carbon sequestration and its vertical distribution in the Chinese Loess Plateau. *PLoSOne,* 7(7), e40123. *https://doi.org/10.1371/journal.pone.0040123*

Johnson, J.M.F., Barbour, N. W. & Lachnicht, W. S. (2007). Chemical composition of crop biomass impacts its decomposition. *Soil Sci Soc American J*, 71(1), 155-162. *https://doi.org/10.2136/sssaj2005.0419*

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O´Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J. & Neves E.G. (2005). Black carbon increases cation Exchange capacity in soils. *Soil Sci Soc American J*, 70(5), 1719-1730. *https://doi.org/10.2136/sssaj2005.0383*

Nascente, A. S., Yuncong, L. & Costa, C. C. A. (2015). Soil aggregation, organic carbon concentration, and edaphic density as affected by cover crop species in a no-tillage system. *Rev Bras Ciênc Solo*, 39(3), 871-879. *http://dx.doi.org/10.1590/01000683rbcs20140388*

Palma, L. D.J., Cisneros, D. J., Moreno, C. E & Rincón, R. J.A. (2007). Suelos de Tabasco: su uso y manejo sustentable. Colegio de Postgraduados-ISPROTAB-FUPROTAB (Eds.) Villahermosa, Tabasco, México. 195 pp.

Ramos-Reyes, R., Sánchez-Hernández, R. & Gama-Campillo, L.M. (2016). Análisis de cambios de uso del suelo en el municipio costero de Comalcalco, Tabasco, México. *Ecosistemas y Recursos,* 3(8), 32-39.

Sánchez-Gutiérrez, F., Pérez-Flores J., Obrador-Olán, J.J., Sol-Sánchez, Á. & Ruiz-Rosado, O. (2016). Árboles maderables en el sistema agroforestal de cacao en Cárdenas, Tabasco, México. *Revista Mexicana de Ciencias Agrícolas,* 14(Sup.), 2711-2723.

Schroth, G., Bede, L.C., Paiva, A.O., Cassano, C.R., Amorim, A.M., Faria, D., Mariano-Neto, E., Martini, A.M. Z., Sambuichi, R.H.R. & Lôbo, R.N. (2015). Contribution of agroforests to landscape carbon storage. *Mitig Adapt Strat Gl*, 20(7), 1175-1190. *http://dx.doi.org/10.1007/s11027-013-9530-7*

Tadakatsu, Y., Ohkura, T. & Matsumoto, N. (2015). Ecosystem Fertility: A new paradigm for nutrient availability to plants in the humid tropics, *Soil Science & Plant Nutrition*, 61(4), 698-703. *http://dx.doi.org/ 10.1080/00380768.2015.1017439*