Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 121 No. 1 (2020) 113–125

https://doi.org/10.17170/kobra-202005281299 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Effects of agroecological practices on soil organic carbon sequestration using synchronic and diachronic approaches in Madagascar

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Abstract

Sequestration of soil organic carbon (SOC) in agricultural systems is a key indicator of soil fertility improvement and climate change mitigation at the global scale. In Madagascar, the effect of management conversion from traditional practices to agroecological ones on SOC sequestration remains unclear. The objectives of this study therefore were (i) to assess the effects of agroecological practices, such as agroforestry (AF), tree plantation (TP) and improved farming practices (IFs), on SOC sequestration at the field level; and (ii) to use both synchronic and diachronic approaches to quantify SOC sequestration following the adoption of agroecological practices. For the diachronic approach, two sampling years (2014 and 2018) were used to determine the annual soil carbon sequestration rates with agroecological practices. For the synchronic approach, SOC sequestration arising from agroecological practices was compared to that of reference fields, such as fallow land (FL) and traditional farming practices (TFs). Soil sampling was carried out on 36 fields with agroecological practices and 60 reference TFs and FL fields. The diachronic approach showed that SOC sequestration rates for AF, TP and IFs were respectively, +2.8, +1.6 and −0.9 t C ha^{-1} yr^{-1}. The synchronic approach showed that SOC stock in AF was higher (109.4 t C ha^{-1}) than in reference TFs (73.8 t C ha^{-1}) and FL (67.4 t C ha^{-1}) fields. The SOC stock in IFs (74.8 t C ha^{-1}) and TP (69 t C ha^{-1}) was not significantly different compared to reference fields. For Madagascar this study provides a better understanding of soil carbon dynamics at the farm level when agroecological practices are adopted in place of traditional practices.

Keywords: agroforestry, compost, MIRS, sequestration rate, tree plantation

1 Introduction

Sequestration of soil organic carbon (SOC) is an important natural process that affects both food security and climate change. SOC plays a fundamental role in the biological and physical functions of soil, as a driver for food production, but also for improved water quality and retention, and for the prevention of soil erosion. Some soil and crop management practices are now widely recognised for their potential to mitigate climate change by stimulating soil organic carbon sequestration (Haddaway *et al*., 2016; Vicente-Vicente *et al*., 2016; Minasny *et al*., 2017). In the tropics, often loss of SOC is due to tillage and conversion of natural vegetation to cultivated land (Lal, 2003). However, soils have a great potential for carbon sequestration when restorative land use and specific management practices are applied (Lal, 2004). The 4 per 1000 Initiative launched at COP21 in Paris suggests the use of agricultural practices adapted to local situations, such as agroecology, agroforestry, conservation agriculture and landscape management, in order to improve organic matter content and promote carbon sequestration in soils (Minasny *et al*., 2017). Agroecology, which is defined as an integrative discipline that includes elements of

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Published online: 16 June 2020 – Received: 17 January 2020 – Accepted: 5 May 2020

agronomy, ecology, sociology and economics (Dalgaard *et al.*, 2003), responds to this challenge of how to manage and sustainably restore agricultural soil fertility. Agroecological practices are also recognised as practices that promote the sustainability of farming systems while optimizing and stabilizing yields (Silici, 2014). However, the impact of such practises on soil carbon sequestration on farms in tropical regions is rarely documented. This is mainly due to the lack of long-term field experiments and technical support provided to farmers for monitoring the implementation of these agroecological practices.

In recent decades in the Itasy Region, central Madagascar, diverse agroecological practices were promoted to farmers to improve their livelihood, through the sustainable management of natural resources, and enhance their income by increasing the diversification of agricultural products. These agroecological practices are mainly agroforestry (AF), tree plantation (TP) and improved farming practices (IFs). Improved farming practices are characterised by the rotation of diverse annual crops fertilised with organic matter such as compost and improved manure. In Madagascar, the environmental impacts of these agroecological practices adopted by farmers were first assessed in terms of soil and biomass carbon sequestration at the plot scale (Razafimbelo *et al.*, 2018; Razakamanarivo *et al.*, 2010), and later, in terms of greenhouse gas fluxes at the farm scale using a carbon footprint approach (Rakotovao *et al.*, 2017). These pioneer studies were all using the "synchronic approach", which means that land use practices implemented over varying durations are compared across a chronosequence of plots sampled at the same point in time (Stewart *et al.*, 2005; Neto *et al.*, 2010). Soil samples are collected at the same time from field plots with different management systems: alternative practices whose history, and especially duration (i.e. the time since the plot's conversion from an initial or reference state), are known; and conventional practices, which represent the reference state (Costa Junior *et al.*, 2013).

The "diachronic approach" is another method used to assess soil carbon sequestration rates (Costa Junior *et al.*, 2013; Fujisaki *et al.*, 2017). It consists of measuring and comparing different land uses or practices on the same plot at two different periods of time. This second approach is considered more reliable than the synchronic approach, but is rarely used, since it involves extended periods of monitoring and related funding constraints. In Madagascar, there are limited field experiments that have long history of land use records. Therefore, to date, the main method used to assess the soil carbon sequestration of the agricultural practices adopted by farmers has been the synchronic approach (Razafimbelo *et al.*, 2018).

This work thus aims to (i) assess the effects of AF, TP and IFs on soil carbon stocks compared to traditional farming practices (TFs) and fallow land (FL), which are taken as reference practices; and (ii) quantify the sequestration rate of soil carbon for these agroecological practices over time. An important innovation of this work is in its comparison of two methods for detecting change: the synchronic and diachronic approaches.

2 Materials and methods

2.1 Site description

The study was conducted in the Itasy Region of the Central Highlands of Madagascar (46°12′E to 47°24′E and 18°36′S to 19°24′S), at an altitude ranging from 800 to 1800 m above sea level. The region is characterised by a tropical altitude climate with two distinct seasons: a dry and cool period lasting from April to October and a warm and humid period from November to March (ONE, 2007). According to the nearest weather station of Ankadinondry Sakay the mean annual precipitation is 112.2 mm with a range of 800 mm to 1,000 mm (based on climate data of 1981 to 2010) during the humid season and 40 mm in the dry season. The mean annual temperature is 21.7 °C with a minimum of 7 °C and a maximum of 28 °C. The region is dominated by two main soil types: Ferralsols in the east and Andosols in the west (FAO, 2003). The region is composed of 20 % irrigated lands for the cultivation of lowland rice (*Oryza sativa*) and 80 % land intended for rainfed agriculture, such as annual crops (rainfed rice, maize (*Zea mays*), cassava (*Manihot esculenta*), beans (*Phaseolus vulgaris*), AF and TP (Rakotovao *et al.*, 2017)).

2.2 Agroecological practices adopted on agricultural fields

In 2014, 36 fields on which farmers had adopted agroecological practices were identified and sampled for soil carbon stock quantification. These innovative practices were for the most part AF, TP, and IFs that had been implemented for 4–6, 9–11 and 4 years, respectively.

In this study agroforestry is defined as the association of annual crops and trees on the same piece of land. Agroforestry sites were fertilised annually by around 9 to 12 tons per hectare of organic matter, such as compost and improved manure (Rakotovao, 2017), every year. Trees planted in TP were forest species for energy production or for timber such as *Melia* sp. (voandelaka), *Eucalyptus* sp. (eucalyptus), *Pinus* sp. (pins) and *Acacia* sp. (acacia). In TP, organic fertiliser (mainly manure) is applied only in the first year of plantation (5 t ha^{-1}). Improved farming practices is characterised by the rotation of different crops such as *Oryza sativa* (rainfed rice), *Manihot esculenta* (cassava), *Ipomoea batatas* (sweet potato), *Zea mays* (maize), *Phaseolus vulgaris* (bean), and *Solanum lycopersicum* (tomato), fertilised with organic matter, such as compost and improved manure at about 9 tons per hectare (Supplementary Data 1).

In 2018 (four years later), these same plots were resampled in order to determine the soil carbon sequestration rate. In addition, the soil carbon stocks of the fields with agroecological practices were compared to those of other fields where traditional farming practices (TFs) were still being used, and a land use reference, such as fallow land (FL). A total of 96 agricultural plots representing both agroecological and traditional practices (Supplementary Data 1) were therefore identified and sampled in this study.

2.3 *Sampling protocol and soil preparation*

To ensure the comparability of the data for both approaches, the same sampling protocol was adopted in both 2014 and 2018. In order to assess the initial soil carbon stock in the farmers' fields, a first soil sampling was carried out in 2014 for AF, TP and IFs sites. In 2018, a second sampling was carried out on the same agroecological plots, adding two other reference plots (TFs and FL). Both samplings were carried out during the same period (July and August) in order to reduce the effects of seasonal variability (temperature, humidity) and the cropping calendar.

In addition, the two dominant soil types (Ferralsols and Andosols) of the Itasy Region were taken into account in order to assess the variability of the soil carbon stock throughout the study area. As Ferralsols predominate in the study area compared to Andosols, two-third of the agroecological plots selected for soil sampling were on Ferralsols and one-third on Andosols. The protocol consisted of collecting soil samples using a manual steel auger at three different depths: 0–10 cm, 10–20 cm and 20–30 cm. Four replications per plot were taken from each depth to obtain composite samples for SOC analysis. Soil samples for bulk density analysis were collected in the middle of each plot at the same three interval depths to the samples for measuring soil carbon content. A manual steel cylinder of 10 cm in height and 8 cm in diameter (502.4 cm^3) was used to collect the soil samples for the bulk density analysis. The composite soil samples collected were air-dried, ground and sieved to 2 mm to remove fine roots.

2.4 *Bulk density analysis*

The soil samples for the bulk density analysis were weighed (fresh weight), oven-dried for 24 hours at 105 °C, and reweighed (dry weight). The bulk density of each depth of soil was calculated using the ratio of dry weight soil and cylinder volume. The dried soils were sieved to remove coarse fraction materials (fine roots and gravel or stone) >2 mm. The weight of these coarse fragments was used to estimate the percentage of coarse fraction which did not contain carbon or belonged to the soil carbon pool (Poeplau *et al.*, 2017).

2.5 *Soil carbon analysis*

The composite soil samples from the agroecological (AF, TP and IFs) plots sampled in 2014 ($n = 108$) and 2018 (($n = 108$) were analysed in the laboratory using the wet oxidation method (Walkley & Black, 1934) for estimating carbon content. For the reference plots' ($n = 108$) soil carbon content at each depth was predicted using mid-infrared spectral (MIRS) models developed for the Itasy Region (Rakotovao *et al.*, 2016). The prediction model for Ferralsols indicated good performance both in calibration ($R^2 = 0.91$, $RPD = 3.19$) and validation ($R^2 = 0.86$, $RPD = 2.72$). The model for Andosols demonstrated excellent performance in predicting soil carbon content in both calibration ($R^2 = 0.97$, $RPD = 6.5$) and validation ($R^2 = 0.86$, $RPD = 2.72$; Supplementary Data 2).

2.6 *Spectral analysis*

The soil carbon content on reference plots was predicted using partial least-squares (PLS) regression models. The composite samples were dried, sieved to 2 mm to remove coarse and inert elements, and ground to 0.2 mm. Mid-infrared spectroscopy (MIRS) was used to scan all ground soil samples at 8 cm^{-1} intervals between 400 and 4,000 cm^{-1} using an Agilent 4100 ExoScan FTIR spectrometer (Danburry, CT, USA). The spectral acquisition collected 64 scans per minute. The spectra data were recorded in the spectral region from 654.753 to 3,999.23 cm^{-1}. A reference spectrum was recorded at the beginning of each spectral acquisition series and once every hour. The spectral data matrix thus consisted of 288 composite samples and 901 variables corresponding to wave numbers and the measured values of absorption.

Two prediction models, one for each soil type (Ferralsols and Andosols) had already been developed to assess soil carbon content in the Itasy Region (sampling year: 2014). In this study, these models were adapted (with the addition of new soil samples collected in 2018) and used to estimate the soil carbon content of reference plots sampled in 2018. The prediction models were computed using 70 % soil sample spectra for the calibration set and 30 % for the validation set.

2.7 Calculation of soil carbon stock and sequestration

The SOC stock for each plot was calculated in t C ha^{-1} using the bulk density values, carbon content, depth and percentage of coarse fraction for each depth. The calculation with k layers was performed as follows:

$$\text{SOC} = \sum_{i=1}^{k} [CC_i \times BD_i \times D_i \times (1 - CF_i)] \quad (1)$$

where *SOC* is the total amount of soil organic carbon per unit area, CC_i (g C kg^{-1}) is the concentration of soil organic carbon in layer i, BD_i (g cm^{-3}) is the bulk density of layer i, D_i (m) is the thickness of layer i, and CF_i is the portion of the volume of coarse fragments >2 mm in layer i (with $0 \leq CF_i < 1$). For each soil profile, the soil carbon stock per plot was calculated for the 0–30 cm soil layer (sum of the SOC for the three 0–10 cm, 10–20 cm and 20–30 cm layers). Soil carbon stock variations in the 0–30 cm layer were calculated using the differences in the carbon stocks for the same plot sampled in 2014 and 2018. The soil carbon sequestration rate, expressed in t C ha^{-1} yr^{-1}, was then calculated by dividing the variation in soil carbon stock by the number of years between samplings (four). Positive carbon sequestration rate values indicate an increase in soil carbon stock, while negative values indicate a reduction in carbon.

2.8 Statistical analysis

Descriptive statistics, comprising means and standard deviations, were calculated to determine bulk density, carbon content and carbon stock for each of the land use and agricultural practices (LUAPs) and soil types to analyse the data variability. An analysis of variance (ANOVA) using the Tukey test ($p < 0.05$) was performed on the results to test the statistical significance of differences between LUAP means and the sampled plot means for each year. Statistical analyses were conducted using R software version R-3.3.2 (R Core Team, 2016).

3 Results

3.1 Soil spectroscopy models for estimating carbon content

The prediction model for Ferralsols indicated good performance both in calibration ($R^2 = 0.91$, $RPD = 3.19$) and validation ($R^2 = 0.86$, $RPD = 2.72$). The model for Andosols demonstrated excellent performance in predicting soil carbon content in both calibration ($R^2 = 0.97$, $RPD = 6.5$) and validation ($R^2 = 0.86$, $RPD = 2.72$.; Supplementary Data 2).

3.2 Bulk density and carbon content statistics

For both 2014 and 2018, bulk density increased with soil depth. Statistical analysis showed that the average bulk density values for each depth did not differ significantly across LUAP and soil types. In Ferralsols, the bulk densities of TP and IFs sites increased significantly from 2014 (1.04 ± 0.14 g cm^3 for TP and 1.04 ± 0.07 g cm^3 for IFs) to 2018 (1.24 ± 0.06 g cm^3 for TP and 1.23 ± 0.19 g cm^3 for IFs) in the first soil layer 0–10 cm (Supplementary Data 3).

Soil carbon contents in the first layer (0–10 cm) of the 2014 sampling did not differ significantly across the LUAP sites (33.7 ± 16 g C kg^{-1} for AF, 24.2 ± 4.6 g C kg^{-1} for TP and 26.7 ± 6.2 g C kg^{-1} for IFs). However, in the 10–20 cm and 20–30 cm layers, soil carbon content was significantly higher on AF plots (31.1 ± 13.6 g C kg^{-1} and 31.9 ± 13.2 g C kg^{-1}, respectively) than on TP (20.3 ± 9.8 g C kg^{-1} in the 10–20 cm layer and 17.5 ± 8 g C kg^{-1} in the 20–30 cm layer) and IFs (22.7 ± 6.7 g C kg^{-1} in the 10–20 cm layer and 20.8 ± 4.4 g C kg^{-1} in the 20–30 cm layer) plots.

For the 2018 sampling, we found that for all soil layers, the carbon content of AF plots was significantly higher than on TP, IFs, TFs and FL. That was observed on both Ferralsols and Andosols (Supplementary Data 3). For the diachronic approach, no significant difference of the soil carbon content was detected between 2014 and 2018 for all LUAP and for all soil layers (Supplementary Data 3).

3.3 Soil carbon stock comparison using the synchronic approach

The soil carbon stocks of plots with adopted agroecological practices (AF, TP and IFs) were compared to reference (TFs and FL) plots. The observed values indicated significant variability across the different LUAPs. The highest value for soil carbon stock at a depth of 30 cm was found on AF plots (109.4 ± 37.1 t C ha^{-1}), this being higher than the values for both TP (69 ± 18.9 t C ha^{-1}) and IFs (74.8 ± 25.4 t C ha^{-1}) plots, and the reference TFs (73.8 ± 32 t C ha^{-1}) and FL (67.4 ± 35.1 t C ha^{-1}) plots ($p < 0.05$; Figure 1).

On Ferralsols, no significant difference was found between the soil carbon stocks of TP (71.3 ± 21.5 t C ha^{-1}), IFs (72.3 ± 25.6 t C ha^{-1}), TFs (69.1 ± 26.8 t C ha^{-1}) and FL (58.1 ± 25.5) plots. On Andosols, although AF showed higher soil carbon stock than TP, IFs and reference plots, the observed differences were not significant at $p = 0.05$ (Figure 1 and Table 1).

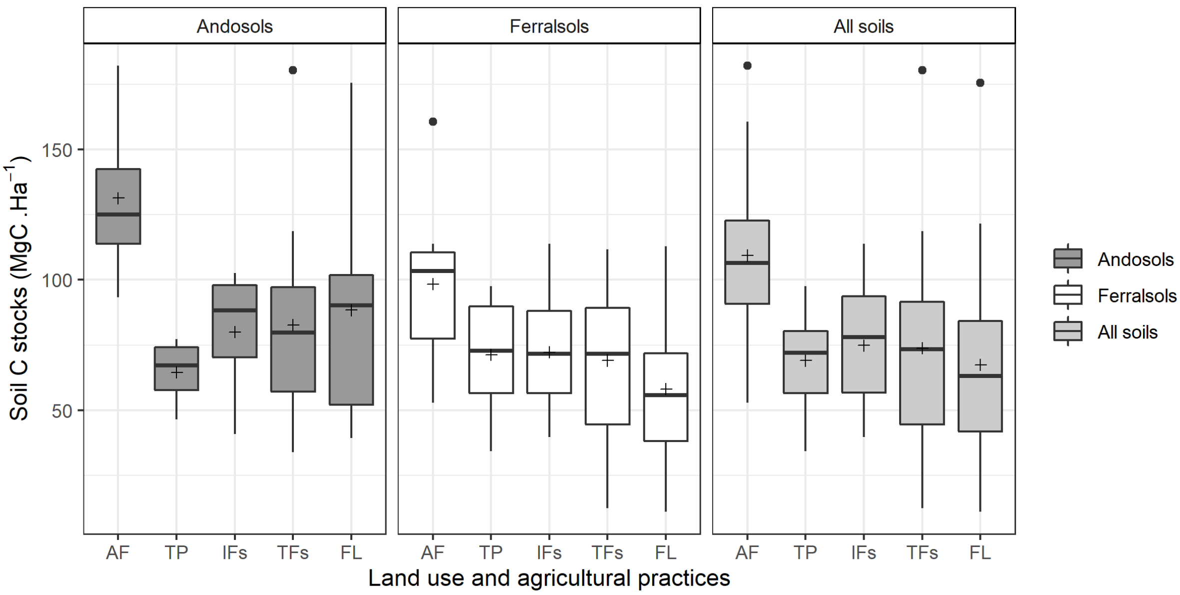

Fig. 1: *Soil carbon stocks of plots with agroecological (AF=agroforestry, TP=tree plantation, IFs=improved farming practices) and reference practices (TFs=traditional farming practices and FL=fallow land) in the Itasy Region of the Central Highlands of Madagascar.* ***Note****: Black lines of boxplots represent 0 and 90 % quantiles, the square box represent 25, 50 and 75 % quantiles, the cross inside the box represents the mean, the black dots represent outliers.*

3.4 Soil carbon stock comparisons using the diachronic approach

The soil carbon stocks of the agroecological plots sampled in 2018 were compared to the same plots sampled in 2014. In other words, the diachronic approach taken in this study allows soil carbon stock dynamics over four years to be assessed.

For AF plots, a systematic increase was observed (Figure 2). The average soil carbon stock for all soil types was estimated at 98.1 (± 43.7) t C ha^{-1} in 2014 and 109.4 (± 37.1) t C ha^{-1} in 2018 at a depth of 30 cm. In Andosols, the soil carbon stock was much higher than in Ferralsols and estimated at 127.4 (± 25.9) t C ha^{-1} in 2014 and 131.4 (± 37.2) t C ha^{-1} in 2018. For Ferralsols, the soil carbon stock in AF plots was estimated at 83.5 (± 44.5) t C ha^{-1} in 2014 and 98.4 (± 33.9) t C ha^{-1} in 2018.

For TP plots, a similar increase in soil carbon stocks from 2014 to 2018 to that of AF plots was observed. On average, the soil carbon stock on TP plots at a depth of 30 cm was estimated at 62.6 (± 21.5) t C ha^{-1} in 2014 and 69 (± 18.9) t C ha^{-1} in 2018. In Andosols, there was an increase from 56.1 (± 20.7) t C ha^{-1} in 2014 to 64.5 (± 13.8) t C ha^{-1} in 2018, while the soil carbon stock in Ferralsols increased from 65.8 (± 22.4) t C ha^{-1} in 2014 to 71.3 (± 21.5) t C ha^{-1} in 2018. This increase in soil carbon stock values was observed in all soil layers (0–10 cm, 10–20 cm and 20–30 cm).

For IFs plots, the average soil carbon stock was found to decrease from 78.5 (± 18.4) t C ha^{-1} in 2014 to 74.8 (± 25.4) t C ha^{-1} in 2018 at a depth of 30 cm. The same trend was observed for both Andosols (82.2 [± 26] t C ha^{-1} in 2014 and 80 [± 27.9] t C ha^{-1} in 2018) and Ferralsols (76.4 [± 14.5] t C ha^{-1} in 2014 and 72.3 [± 25.6] t C ha^{-1} in 2018).

3.5 Soil organic carbon stock dynamics

The soil carbon sequestration rates for agroecological (AF, TP and IFs) plots were obtained by calculating the difference between soil carbon stocks in 2018 and 2014 for each field plot and each LUAP. This difference was then divided by the number of years (four) between the two assessment periods (2014 and 2018). AF and TP plots had positive soil carbon sequestration rates, which were estimated at +2.8 and +1.6 t C ha^{-1} yr^{-1}, respectively. AF fields located on Ferralsols had a higher carbon sequestration rate (+3.7 t C ha^{-1} yr^{-1}) than those located on Andosols (+1.0 t C ha^{-1} yr^{-1}). For TP fields, however, the carbon sequestration rate on Andosols (+2.1 t C ha^{-1} yr^{-1}) was higher than on Ferralsols (+1.4 t C ha^{-1} yr^{-1}). Thus, the agroecological practices AF and TP increased soil carbon stock between 2014 and 2018 (Figure 3, Table 1). IFs fields produced a negative soil carbon sequestration rate, estimated at −0.9 t C ha^{-1} yr^{-1}. For both Ferralsols and Andosols, the carbon sequestration rates of IFs fields were estimated at −0.6

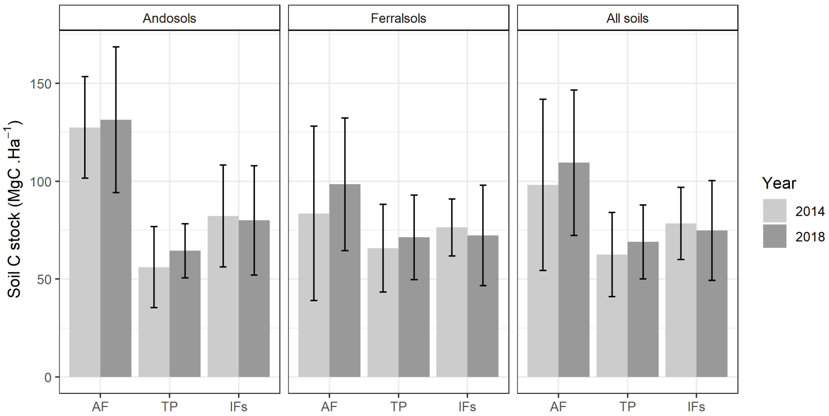

Fig. 2: *Soil organic carbon stock (0-30 cm) of plots with different agroecological practices in the Itasy Region of the Central Highlands of Madagascar (AF = agroforestry, TP = tree plantation, IFs = improved farming practices).*
***Note**: Bars indicate mean and black line represent ±standard deviation.*

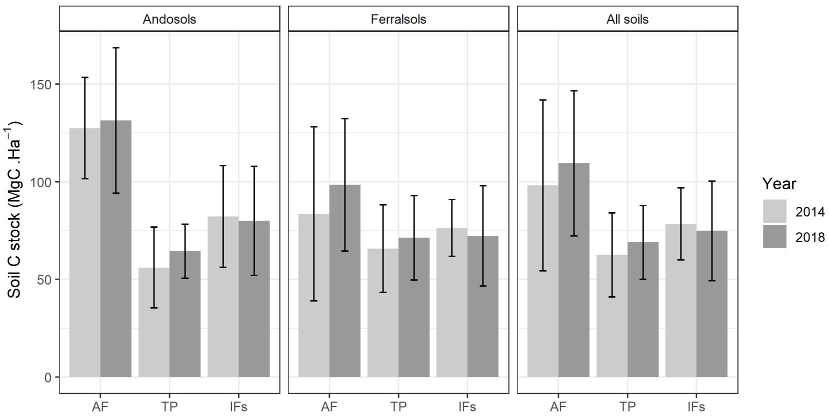

Fig. 3: *Soil carbon sequestration rates of agroecological plots between the 2014 and 2018 samplings (AF = agroforestry, TP = tree plantation, IFs = improved farming practices).*
***Note**: Black lines of boxplot represent 0 and 90 % quantiles, the square box represents 25, 50 and 75 % quantiles, the cross inside the box represents the mean.*

and −1.0 t C ha^{-1} yr^{-1} respectively. This represents a reduction in soil carbon on IFs plots from 2014 to 2018 (Figure 3).

4 Discussion

4.1 Potential of agroforestry to store carbon in the soil

This study shows the potential of agroforestry to store carbon in soils at up to 1.0 t C ha^{-1} yr^{-1} in Andosols and 3.7 t C ha^{-1} yr^{-1} in Ferralsols at depths of 0–30 cm. Previous research conducted in the tropics has shown that agroforestry is one of the most carbon sequestering practices in terms of both soil and biomass (Albrecht & Kandji, 2003; Hutchinson *et al.*, 2007; Feliciano *et al.*, 2018). In Africa, the AF systems with the highest mean soil carbon sequestration rates were in improved fallow, estimated at 1.91 (± 3.42) t C ha^{-1} yr^{-1} and in shadow systems, estimated at 1.91 (± 13.01 t C ha^{-1} yr^{-1}. In other tropical regions, the soil carbon sequestration rate of AF systems can reach up to 6.54 (± 2.99) t C ha^{-1} yr^{-1} in Latin America (silvopastoral system) and 3.83 (± 2.36) t C ha^{-1} yr^{-1} in Asia homegarden (Feliciano *et al.*, 2018).

The AF systems adopted by farmers in Madagascar's Itasy Region can be defined as agrisilvicultural homegarden systems (ibid.). On average, agrisilvicultural systems were reported to store 0.32 t C ha^{-1} yr^{-1} in Africa, 0.27 t C ha^{-1} yr^{-1} in Asia and 1.73 t C ha^{-1} yr^{-1} in Latin America. For homegarden systems, soil carbon sequestration rates in Africa and Asia are estimated at 0.19 and 3.83 t C ha^{-1} yr^{-1}, respectively (ibid.).

Table 1: *Soil carbon stocks of fields with different land uses and agricultural practices (LUAPs) using synchronic and diachronic approaches, and soil carbon sequestration rates (t C ha^{-1}yr^{-1}) of fields with agroecological practices in the Itasy Region of the Central Highlands of Madagascar.*

*LUAP**	*n*	*2014*			*2018*			*2014*	*2018*	*Mean annual C accumulation*
		0–10 cm	*10–20 cm*	*20-30 cm*	*0–10 cm*	*10–20 cm*	*20-30 cm*	*0–30 cm*	*0–30 cm*	(t C ha^{-1}yr^{-1})
All samples (t C ha^{-1}yr–1)										*All samples*
AF	12	33.4 (±15.9)^{Aa}	31.4 (±15.4)^{Aa}	33.3 (±14.3)^{Aa}	39.3 (±15)^{Aa}	38.7 (±16.1)^{Aa}	31.4 (±13.2)^{Aa}	98.1 (±43.7)^{Aa}	109.4 (±37.1)^{Aa}	2.8
TP	12	24.6 (±4.5)^{Aa}	19.6 (±11.1)^{Aa}	18.3 (±11.2)^{Ba}	27.2 (±5.7)^{Ba}	23.2 (±6.7)^{Ba}	18.6 (±8)^{Ba}	62.6 (±21.5)^{Ba}	69.0 (±18.9)^{Ba}	1.6
IFs	12	28.5 (±7.7)^{Aa}	25.8 (±8.5)^{Aa}	24.2 (±5.5)^{ABa}	25.9 (±9.5)^{Ba}	25.5 (±8.8)^{Ba}	23.5 (±8.1)^{ABa}	78.5 (±18.4)^{ABa}	74.8 (±25.4)^{Ba}	−0.9
TFs	36	-	-	-	26.7 (±10.9)^{B}	24.3 (±11.8)^{B}	22.8 (±11.5)^{AB}	-	73.8 (±32.0)^{B}	-
FL	24	-	-	-	25.0 (±12.9)^{B}	22.9 (±12.9)^{B}	19.5 (±11.3)^{B}	-	67.4 (±35.1)^{B}	-
Ferralsols (t C ha^{-1}yr–1)										*Ferralsols*
AF	8	29.5 (±18.2)^{Aa}	26.6 (±14.5)^{ABa}	27.4 (±12.9)^{Ba}	34.4 (±13.6)^{Aa}	36.7 (±17.3)^{Aa}	27.3 (±13.2)^{Aa}	83.5 (±44.5)^{Ba}	98.4 (±33.9)^{Aa}	3.7
TP	8	24.2 (±3.9)^{Aa}	21.7 (±12.2)^{ABa}	19.9 (±8.4)^{Ba}	28.1 (±6.6)^{ABa}	23.3 (±8.1)^{Ba}	19.9 (±8.1)^{Aa}	65.8 (±22.4)^{Ba}	71.3 (±21.5)^{Ba}	1.4
IFs	8	27.6 (±8.9)^{Aa}	24.4 (±5.3)^{ABa}	24.3 (±4.3)^{Ba}	23.9 (±10)^{Ba}	25.0 (±8.2)^{Ba}	23.4 (±8.1)^{Aa}	76.4 (±14.5)^{Ba}	72.3 (±25.6)^{Ba}	−1.0
TFs	24	-	-	-	25.0 (±9.5)^{AB}	22.6 (±10.3)^{B}	21.5 (±10.2)^{A}	-	69.1 (±26.8)^{B}	-
FL	16	-	-	-	21.1 (±9.8)^{B}	20.0 (±10.5)^{B}	16.9 (±8.2)^{A}	-	58.1 (±25.5)^{B}	-
Andosols (t C ha^{-1}yr–1)										*Andosols*
AF	4	41.3 (±5.6)^{Aa}	41 (±14)^{Aa}	45.1 (±9.2)^{Aa}	49.3 (±14)^{Aa}	42.6 (±14.6)^{Aa}	39.5 (±10)^{Aa}	127.4 (±25.9)^{Aa}	131.4 (±37.2)^{Aa}	1.0
TP	4	25.2 (±6)^{Aa}	15.6 (±8.3)^{Ba}	15.2 (±16.6)^{Ba}	25.3 (±3.1)^{Aa}	23.0 (±3.7)^{Aa}	16.1 (±8.3)^{Aa}	56.1 (±20.7)^{Ba}	64.5 (±13.8)^{Aa}	2.1
IFs	4	29.9 (±6)^{Aa}	28.4 (±13.1)^{ABa}	23.9 (±7.9)^{Ba}	29.8 (±8.2)^{Aa}	26.5 (±11.1)^{Aa}	23.7 (±9.5)^{Aa}	82.2 (±26)^{Ba}	80.0 (±27.9)^{Aa}	−0.6
TFs	12	-	-	-	29.8 (±13)^{A}	27.7 (±14.1)^{A}	25.2 (±13.9)^{A}	-	82.7 (±39.9)^{A}	-
FL	8	-	-	-	33.7 (±15.4)^{A}	29.3 (±16.0)^{A}	25.4 (±15.5)^{A}	-	88.5 (±45.8)^{A}	-

Values in brackets refer to the standard deviation. Uppercase letters show results of ANOVA test comparing LUAPs at same depth and using synchronic approach (same letters accompanying the values indicate they are not significantly different at $p<0.05$). Lowercase letters show results of LUAP comparison at same depth using diachronic approach.

* LUAPs: AF = agroforestry, TP = tree plantation, IFs = improved farming practices, TFs = traditional farming practices, FL = fallow land.

Based on the original land use before adopting AF practices (TFs and FL), the soil carbon sequestration rate of AF in the Itasy Region (2.8 t C ha^{-1} yr^{-1}) can be compared with classifications in the literature (e.g. IPCC 2006) such as "cropland to agroforestry", for which the soil carbon sequestration rate was estimated to be 1.25 ± 0.04 t C ha^{-1} yr^{-1} (Cardinael *et al.*, 2018). Crop management and the characteristics of the systems adopted in the Itasy Region may explain AF's high potential for storing carbon in the soil. Firstly, the density of plantation, estimated at 200–500 trees per hectare, enhances the soil carbon accumulation rate due to high biomass production and carbon inputs (Peichl *et al.*, 2006; Cardinael *et al.*, 2018; Corbeels *et al.*, 2018). The diversity of tree species also improves the benefits obtained from roots exploring the different soil layers. Trees with developed root systems can recover nutrients from deeper soil layers and thus improve soil nutrient availability and uptake, while at the same time activating soil microbial activities improve the decomposition and mineralisation of organic matter (Nair, 1993). Additionally, the annual crops planted alongside trees (*Coffea arabica*, *Citrus* sp., *Litchi chinensis*, *Mangifera indica* and *Persea americana*) in AF systems benefit from a significant supply of organic fertiliser, estimated at 5 to 9 t C ha^{-1}, comprising mainly compost and improved manure (Rakotovao, 2017).

According to Laganiere *et al.* (2010), age of the agroforestry system is also one of the factors that most influences soil carbon sequestration rates. Studies by Kim *et al.* (2016) found that agroforestry systems resulted in a significant increase in soil organic carbon in the first year after their implementation (up to 7.4 t C ha^{-1} yr^{-1} in areas of silvopasture and rotational woodlots) before gradually diminishing over time. The average soil carbon sequestration rate of young stands (14 years old on average) was estimated at 2.2 ± 1.2 t C ha^{-1} yr^{-1} for agroforests with tree-crop coexistence in which trees and agricultural crops are grown together (ibid.). This is consistent with the sequestration rate for agroforestry systems in the Itasy Region (2.8 t C ha^{-1} yr^{-1}) of 8–10 years in age.

4.2 Soil carbon stock increases following tree planting

Tree planting resulted in increased carbon sequestration both in Ferralsols (1.4 t C ha^{-1} yr^{-1}) and Andosols (2.1 t C ha^{-1} yr^{-1}). TP plots dominated by *Eucalyptus* sp., *Pinus* sp., *Acacia* sp. and other native species provided farmers with additional income thanks to the wood they produced (for building houses, firewood, etc.). An additional objective of tree planting was to restore degraded land not currently used for agriculture.

On average, the soil carbon stock on TP plots was estimated at 62.6 (± 21.5) t C ha^{-1} in 2014 and 69 (± 18.9) t C ha^{-1} in 2018. These values are lower than those for eucalyptus coppices in the Central Uplands of Madagascar, which were estimated at 74,2 ± 15,6 t C ha^{-1} (Razakamanarivo *et al.*, 2010). The reasons for this are mainly associated with the age and planting density of these forestry systems. The values reported by Razakamanarivo *et al.* (2010) were for eucalyptus coppices aged between 20 and 111 years, while the forestry systems of the Itasy Region included in this study were younger: between 10 and 15 years old. Planting density may also be a factor explaining this difference in soil carbon stock, due to the amount of biomass introduced to the soil (Laganiere *et al.*, 2010). The planting density of the eucalyptus coppices in the Central Uplands of Madagascar is approximately 1,500 to 6,300 trees per hectare, while the planting density of TP fields in the Itasy Region was estimated to be between 500 and 1,200 trees per hectare.

In the Itasy Region, TP plots of between 10 and 15 years in age increased their soil carbon stock by up to 1.6 t C ha^{-1} yr^{-1}. This indicates the potential of this system to improve soil quality and restore degraded land whether on Ferralsols (1.4 t C ha^{-1} yr^{-1}) or Andosols (2.1 t C ha^{-1} yr^{-1}). In terms of changes in land use, TP refers to the conversion of fallow land (degraded soil) or cropland (agricultural land), defined here as TFs to TP. A meta-analysis focusing on soil carbon stocks after changes in land use reported that conversion from cropland to tree plantation increased soil carbon sequestration by on average 18 % compared with the initial land use at a maximum of 50 years after trees were planted (Guo & Gifford, 2002). In subtropical climates, an increase in soil carbon stock of up to 35 % (compared with the initial soil carbon stock) has been reported 11 years after the reforestation and afforestation of cultivated lands (Johnson, 1992; Bashkin & Binkley, 1998). In tropical climates, a soil carbon sequestration rate estimated at between 0.8 and 2 t C ha^{-1} yr^{-1} was reported following the reforestation of agricultural land (Lugo & Sanchez, 1986; Brown & Lugo, 1990) and cane fields at a depth of 25 cm (Zou & Bashkin, 1997). Although soil carbon stock decreases over the first 5 to 10 years after tree planting, it then increases after 10 to 30 years (Epron *et al.*, 2009; Laganiere *et al.*, 2010; Han *et al.*, 2017), recovering more soil carbon than in the previous agricultural soil (sequestration rate estimated at 0.37 % per year for depths <30 cm; Paul *et al.*, 2002). Whether established on degraded land or fallow land, TP in the Itasy Region increase soil organic carbon stock, improving soil quality. In fact, soil organic carbon is the main indicator of soil quality, as it determines a soil's physical, chemical and biological properties (Wang *et al.* 2003; Girmay & Singh, 2012).

4.3 Effects of improved farming practices on soil carbon sequestration

Improved farming practices (IFs) involve the rotation of rainfed cereals, cassava, legumes and vegetables, which are fertilised by a recommended 9–12 t C ha^{-1} of organic matter, such as compost and improved manure. In this study, IFs were compared to TFs, which consist of the same crop rotation but with less organic fertilisation (<5 t of farm manure per hectare). The synchronic method revealed that the soil carbon stock on IFs fields was around 74.8 (± 25.4) t C ha^{-1} while on TFs fields it was estimated at 73.8 (± 32.0) t C ha^{-1}. This difference is not statistically significant, although it is recognised that changes in organic soil carbon stock on cropland are mainly driven by organic matter inputs (Fujisaki *et al.*, 2018). This can be explained by farmers' limited capacity to apply the up to 12 t of compost per hectare recommended for IFs fields. Indeed, it has been observed that the recommended compost and improved manure was not applied systematically every year but depended on the availability of organic matter.

The diachronic approach showed that soil carbon sequestration on IFs fields from 2014 to 2018 was negative (−0.9 t C ha^{-1} yr−1) in both Ferralsols (−1.0 t C ha^{-1} yr−1) and Andosols (−0.6 t C ha^{-1} yr−1). This result is consistent with the synchronic approach, which could be explained by the limited capacity of Malagasy farmers to meet the recommended amounts of organic fertiliser.

Furthermore, in the literature, the effective increase in soil carbon sequestration on tropical cropland is the result of the combination of diverse management practices, such as reduced tillage, organic fertilisation (reducing mineral fertilisation) and cover crops, rather than of a change of only one practice (Fujisaki *et al.*, 2018). This increase was estimated at 0.41 ± 0.03 t C ha^{-1} yr−1 on average on tropical cropland (ibid.).

Nevertheless, negative soil carbon sequestration rates have also been reported in the literature by different studies in the tropics following improvements in management practices (Mann, 1986; Johnson, 1992; Reicosky *et al.*, 1997; Manna *et al.* 2005; Razafimbelo *et al.*, 2010; Fujisaki *et al.*, 2018). The reasons for those negative values were not always clear, but mainly concerned duration of study experiments, soil types associated with an initially low carbon content, and crop associations. In the case of our study, the soil carbon loss on IFs fields was mainly the result of farmers' limited capacity to implement the recommended practices. In addition to which, monitoring of the implementation of IFs at the farm level (application of 9–12 t per hectare of compost and improved manure) was not carried out strictly between the sampling years (2014 and 2018). For Malagasy farmers, manure and compost are generally intended for rice fields, as rice cultivation is the number one staple food in Madagascar. Therefore, the amount of organic fertiliser produced by farms may be insufficient for other annual crops such as those grown on IFs fields. Moreover, the average number of cattle (around three cows per farm) limits the annual production of manure and compost for IFs fields (Rakotovao, 2017).

4.4 Carbon sequestration and soil type

The results presented here show that SOC stocks are higher in Andosols than in Ferralsols at a depth of 30 cm. The nature of these soil types may explain this difference. Andosols are defined as SOC-rich soil (Homolák *et al.*, 2017), while Ferralsols are considered SOC-poor and highly vulnerable to SOC loss (Nye & Greenland, 1960; Hartemink, 1997). Andosols are characterised by the presence of amorphous silica such as allophane that protect the stable organic matter in the soil and fix phosphorus (Chevallier *et al.*, 2007). In Ferralsols, which are characterised by low activity clay, soil carbon content is strongly dependent on soil texture (Feller & Beare, 1997; Razafimbelo, 2005). Given that the organic matter inputs added to Malagasy soils are minimal, it would be expected that Ferralsols with low initial carbon stocks accumulate more carbon than Andosols due to their greater SOC saturation deficit (Hassink, 1997; Feng *et al.*, 2013; Fujisaki *et al.*, 2018). Indeed, our study indicated that Ferralsols had a higher carbon sequestration rate than Andosols, as the average sequestration rates for all LUAPs in Ferralsols and Andosols were 1.4 and 0.9 t C ha^{-1} yr−1, respectively.

4.5 Comparison of synchronic and diachronic approaches

The results of both approaches show a similar pattern of soil carbon sequestration on AF and TP plots. Both land uses were found to be sequestering practices under both the diachronic and synchronic approaches. For IFs plots, a decrease in C stocks was observed using the diachronic approach and no significant increase using the synchronic approach. The diachronic and synchronic approaches should produce approximately the same results (Costa Junior *et al.*, 2013; Fujisaki *et al.*, 2018). However, the synchronic approach may create considerable uncertainty due to the range of soils and farming practices across the agroecological and reference plots (Neto *et al.*, 2010; Swanepoel *et al.*, 2016; Feyisa *et al.*, 2017). According to the literature, and taking into account the fact that the diachronic approach is more accurate, it seems more powerful for assessing soil carbon sequestration than the synchronic method (Stewart *et al.*, 2005; Dimassi *et al.*, 2014; Olson *et al.*, 2014; Paustian, 2014; Lal *et al.*, 2015). The major disadvantage of the diachronic approach is that the observer must wait and measure over many years before being able to estimate the amount of C sequestered. Based on the results presented here, a long-term study, looking at practices over a period of 10 years, is required to verify the suggested significant cumulative changes in C stock as a consequence of changing management (López-Fando & Pardo, 2011; Zhang *et al.*, 2016; Ghosh *et al.*, 2018; Liu *et al.*, 2018).

5 Conclusions

The study showed that the diachronic and synchronic approaches show similar trends in terms of soil carbon storage for agroecological practices when these are compared to reference situations. The data also demonstrate the potential of agroforestry and tree planting to increase and maintain carbon stock in both Ferralsols and Andosols. The soil carbon sequestration rate on AF and TP plots was estimated to be 2.8 and 1.6 t C ha^{-1} yr−1, respectively.

Although no significant differences were observed between soil carbon stocks on fields with agroecological practices at depths of 0–30 cm between 2014 and 2018, the data show that AF and TP have a high potential to increase soil carbon stock compared to reference (TFs and FL) plots. However, a field's soil carbon sequestration depends on the amount of organic fertiliser (compost, improved manure, or both) applied, the diversity of tree species (fruit species, native and exotic tree species) and the tree planting density (200 to 1,500 trees per hectare). The uneven availability of organic matter at the farm level has limited the supply of organic fertiliser to rainfed annual crops, resulting in soil carbon losses for IFs fields. Therefore, in the Itasy Region of the Central Highlands of Madagascar, promotion of AF and TP practices on agricultural fields can contribute to climate change mitigation and food security.

Supplement

The supplement related to this article is available online on the same landing page at: https://doi.org/10.17170/kobra-202005281299 .

Acknowledgements

The study is part of the MAHAVOTRA project, funded by the AFD (Agence Française de Développement), La Région Aquitaine and the CEAS, and implemented by Agrisud International, Amades, Nitidae and the CEAS. We also thank farmers and Agrisud International team for their collaboration.

Conflict of interest

Authors state they have no conflict of interest.

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