SOIL ORGANIC CARBON CHANGES FOLLOWING DEGRADATION AND CONVERSION TO CYPRESS AND TEA PLANTATIONS IN A TROPICAL MOUNTAIN FOREST OF KENYA

Short title: **SOIL CARBON DYNAMICS IN PLANTATIONS AND DEGRADED FOREST SITES**

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Abstract

Aims: This study investigates, in a montane forest in Kenya, the changes in amount and stability of soil organic carbon (SOC) as a consequence of: a) forest degradation, by comparing primary and degraded forests; b) the replacement of degraded forests with cypress and tea plantations, by considering sites installed at different time in the past.

Methods: The SOC concentrations and stocks were determined in different layers to 1 m depth, and the SOC turnover time (TT) derived by measuring the ^{14}C concentration in the layers within the 0-30 cm depth.

Results: A significant SOC decline was evident in the 0-5 and 5-15 cm layers of degraded forest while, on the long term, both plantations induced a significant SOC increase in the 0-30 cm depth. The longer TT´s and lower SOC concentrations in the upper layers of degraded rather than primary forests imply an impact of forest degradation on the decomposition of the fast cycling SOC. Similarly, the shorter TT with increasing plantations age implies differences in SOC stabilization mechanisms between plantations and forests.

Conclusions: Cypress and tea plantations established on degraded forests stimulate a long term SOC accrual but at the same time decrease the stability of the SOC pool.

Introduction

Most of the land use change in the tropical regions is triggered by the need to clear forests and woodlands to provide agricultural lands (Houghton et al. 2012) and to satisfy the growing demand for timber, fibre and biofuel (Abood et al. 2015; Aragão et al. 2014). As a result, tropical forests are under severe stress (Lawrence and Vandecar 2015), thereby being the dominant land use/land cover change-induced source of greenhouse gases in the pan-tropics (Roman-Cuesta et al. 2016). Most of the net carbon (C) flux into the atmosphere due to land use change is attributable to deforestation, whereas forest degradation is believed to contribute to a lower extent (Roman-Cuesta et al. 2016;

Houghton et al. 2012). Despite progress has been made in quantifying C losses due to anthropogenic pressure (Parrotta et al. 2012), the interest in the C balance of the tropical areas and especially the impact of deforestation and forest degradation on the C cycle remains high (Aragão et al. 2014; Grace et al. 2014; Valentini et al. 2014).

In tropical areas, soils represent an important C reservoir storing in the uppermost meter about 500 Pg C, an amount equivalent to that present in the phytomass (Scharlemann et al. 2014) or about 30 per cent of all C stored in soils worldwide (Batjes 2016). Nevertheless, the effect of replacing native forests with tree plantations on soil organic carbon (SOC) levels is still unclear especially for the African continent (Marín-Spiotta and Sharma S. 2013; Don et al. 2011; Vägen et al. 2005).

Apart from the most common fast growing tree species (e.g. pine spp, eucalyptus spp, cypress spp) used for plantations in the tropical area, tree cash crop plantations of species such as tea (*Camellia sinensis* L.), are expanding at the expense of areas originally occupied by forests. Currently, tea plantations cover an area of approximately five million hectares globally (FAO 2015a). Research conducted on tea plantations is primarily focused at increasing the production or improving the tea quality (Nepolean et al. 2012), or reducing/constraining soil erosion (Sahoo et al. 2016), while only few studies deal with SOC storage of tea plantations (Chen et al. 2016a; Wang et al. 2016). In general, studies dealing with the SOC change following establishment of tree cash crop plantations on former forest soils are contradictory as some report a SOC decline (Guillame et al. 2015; Chiti et al. 2014; Bravo-Espinosa et al. 2012), while others found no differences (Frazão et al. 2013).

The Mau Forest Complex (MFC), Kenya, represents the largest indigenous tropical montane forest in East Africa. The MFC has undergone a significant land use change due to increased human population demanding land for settlement and agriculture, leading to a considerable land fragmentation and deforestation. In the last fifteen years alone more than 100,000 ha (approximately 25 per cent of the MFC area) have been converted from forest to tree plantations (e.g. cypress and pine*)*, to perennial tree cash crop plantations (e.g. tea) and to smallholder agriculture (Kipkoech et al. 2011). Forest degradation is mainly occurring as a result of illegal charcoal burning, uncontrolled cattle grazing and illegal extraction of forest goods, which are responsible for the degradation of 25 to 40 percent of the forestland during the last decade (Kipkoech et al. 2011).

Based on these considerations, the main aim of this study was to evaluate, within the MFC, the consequences of forest degradation and the replacement of degraded forests with cypress and tea plantations on the SOC levels. Particularly we aimed to: a) evaluate the impact of forest degradation in term of SOC changes by comparing intact and degraded forests; b) assess the directions of SOC changes following deforestation over time, and c) investigate the possible modifications in the stability of the SOC pool as a result of the replacement of the forests using SOC ^{14}C measurements to derive the turnover time (TT).

Materials and Methods

Area description

The study area is located in the South-Western block of the MFC (Figure 1), close to Kericho town (0°S, 35 °E) at an altitude of 2200 m a.s.l. The mean monthly temperatures range from 16 °C in July to 22 °C in September, while the mean annual precipitation is 2200 mm (observation period 1957-2011; Chepkoech et al. 2015). The topography is predominantly rolling hills and the dominant soils are Ferralsols and Cambisols (IUSS Working Group WRB 2014).

Experimental design and soil sampling

Two chronosequences were identified within the MFC. The most common species used for tree (*Cupressus lusitanica* Mill. - cypress) and for tree cash crop plantations (*Camellia sinensis* (L.) Kuntze - tea) were considered. A degraded forest area was identified within those affected by forest degradation, which are mapped in the MFC (Bewernick 2016; Olang and Kundu 2011). Forest degradation was confirmed in the field by the appreciable signs of illegal logging, charcoal burning activities (i.e. presence of recent stumps and charcoal pits residues) and gaps in the canopy cover

(Arias-Navarro et al 2017). The degraded forest area was used as a starting point of the two chronosequences, since both the cypress and tea plantations were established on degraded forest areas, as it is commonly the case. Further, a primary forest area was identified for assessing the effect of forest degradation on the SOC levels by comparison with the degraded forest. Primary forest is defined here as natural forest vegetation without apparent and reported human impacts. Using the management plan of the Kenyan forest service, we identified three cypress plantations, established at different times in the past (20, 38 and 53 years before). Likewise, the Tea Research Institute - located within the MFC - provided access to three tea plantation areas that were established at different times in the past (19, 31 and 43 years before). All sites were included within an area of five km^2 and within an altitude of 2150-2300 m a.s.l. Site preparation for plantations purposes differs between cypress and tea. When establishing a cypress plantation, stumps and roots are manually removed and seedlings are planted at regular grid of 2.5 m × 2.5 m (1600 trees ha^{-1}), followed by weeding during the first years after planting. For establishing a tea plantation, the vegetation is cleared one season ahead by girdling the trees followed by uprooting the stumps including roots and leaving the residues to decompose in situ. Due to the intervention, soil pits are formed, which are subsequently filled up with excavated soil and the ground is levelled. The drains are then laid out and excavated soil spread thinly over the ground (Wilsson and Clifford 1992).

At each site, one-hectare plot was established. Ten samples of the organic horizon, namely the litter layer, were collected in each plot placing a frame of 0.4 m x 0.4 m onto the soil and picking all the organic material within its area. Three soil pits were randomly opened on three of those spots down to 1 m depth and soil samples were collected at 0-5, 5-15, 15-30, 30-50, 50-70 and 70-100 cm depth, using a stainless steel cylinder of fixed volume (diameter=5 cm; height=5 cm) so to determine also the soil bulk density. In the seven additional sampling points where the litter layer was sampled, soil was collected at the same depths using an auger, yielding 10 replicated samples per each layer.

Laboratory analysis and SOC stock estimation

All samples were oven-dried (60 °C) to constant mass. The mineral soil was sieved at 2 mm mesh size; the organic horizon and the mineral soil samples were ground in a ball mill. Three random samples per layer from each plot were used to determine the particle size distribution (Mikutta et al. 2005) and the soil pH by potentiometers in deionised water solution. In all soil samples (n=10 per layer) the total C was measured on finely ground aliquots by dry combustion (Thermo-Finnigan Flash EA112 CHN, Okehampton, UK), and corresponded to organic C given the absence of carbonates in these soils. The SOC stock was calculated for each soil layer according to Boone et al. (1999). Due to the lack of stones, no correction was needed. Changes in SOC stock for the mineral soil were reported for two main compartments: the 0–30 cm depth (topsoil), and the 30–100 cm depth (subsoil). The former was selected in line with the minimum depth required by the IPCC guidelines (IPCC 2006), while the latter, to report complete data down to 1 m depth.

Differences in C concentrations and C stocks were determined among all the sites of each chronosequence and within each site using analysis of variance (ANOVA) with depth treated as a repeated measure using the R software. When significant differences were observed a multiple comparisons test (Tukey HSD) was done. Statistical significance for the ANOVA and Tukey test were established at $p<0.05$.

Radiocarbon measurements and SOC turnover time

A composite sample (n=10) of each of the topsoil depths (0-5, 5-15 and 15-30 cm) from each of the eight plots underwent ^{14}C determination by Accelerator Mass Spectrometer (AMS). Briefly, an aliquot of sample assuring a mass of C ≥ 1 mg was weighed in a pre-cleaned quartz tube filled with copper oxide. Tubes were evacuated to 10^{-5} Pa, flame sealed and placed in a muffle oven at 920 °C for 6.5 hours to achieve complete combustion. The released CO_2 was cryogenically purified from other combustion gases, barometrically quantified, and trapped into Pyrex reactors assembled according to Marzaioli et al. (2008) to produce Zn reduced graphite over iron powder catalyst (at

560 °C for 8 hrs). Graphite was pressed in Al cathodes and measured by means of 3MV CIRCE (Centre for Isotopic Research on Cultural and Environmental heritage of the second University of Naples, Italy) AMS system. Unknown samples were measured in a wheel together with: i) machine (n=4) and preparation blanks (n=3) to correct for background; ii) Oxalic Acid II (OXII) samples (n=4) to normalise measured ^{14}C ratios to absolute values; iii) cellulose (IAEA C3) samples (n=2) and wood (IAEA C5) standards (n=1) to check for the accuracy of the entire procedure (Terrasi et al. 2008). ^{14}C concentrations were measured by means of 3MV CIRCE (Centre for Isotopic Research on Cultural and Environmental heritage of the second University of Naples, Italy) AMS system. The results were expressed as percent Modern (pM) according to Stuiver and Polach (1977). Samples with a pM greater than 97.5 revealed the presence of ^{14}C produced by nuclear weapons testing in the 1950s and 1960s (‘‘bomb C’’). By contrast, pM values lower than 97.5 indicated that the sample incorporated minor amounts of “bomb C”.

The turnover time of the analysed samples was determined from the ^{14}C concentrations, using both a time-dependent steady-state (TDSS) and a non-steady-state (TDNSS) model (Gaudinski et al. 2000). The TDNSS model was used for the degraded forest and the youngest and intermediate-age plantations, while the TDSS model was used for the primary forest and the oldest cypress and tea plantations, which were assumed to be at steady state.

The TDSS model relies on several important assumptions: a) being at the steady state, i.e. where the C inputs and C losses are equal; b) the ^{14}C signature of SOC at any time depends on the ^{14}C signature of the atmosphere in previous years; c) the time-lag between the ^{14}C value of the atmosphere and new inputs to a given pool is one year in the primary forest (deciduous species) and the 43-year-old tea plantation, while for the 53-year-old cypress plantation a time lag of five years was assumed (Lisanework and Michelsen 1994); d) all C atoms in a given pool have the same probability of leaving that pool (i.e., normal distribution of TT within a pool), and e) any given pool is homogenous in terms of ^{14}C signature.

An atmospheric radiocarbon dataset of the bomb-spike period (1950-2010) was developed from Hua and Barbetti (2013) for the southern hemisphere (SH3 zone), annually averaging all available data to smooth the seasonal variability of atmospheric ^{14}C. Data gap filling and extrapolation from 2010 to 2014 for the SH3 zone was performed using the best fitting function. A pre-bomb dataset for the SH3 zone was obtained from Levin and Hesshaimer (2000).

Radiocarbon concentrations on the bomb-spike curve result in two possible TTs on the opposite sides of the ^{14}C peak (Marín-Spiotta et al. 2008). In our case, this occurred only in the 0-5 cm layer. We identified the more likely of the two solutions based on the aboveground litterfall rates and the C stock of that specific soil layer, according to McFarlane et al. (2013) and Marín-Spiotta et al. (2008). For example, a ^{14}C pM value of 104.6% for the 0–5 cm layer in the primary forest corresponded to two possible TTs, 3 years and 183 years. The consideration that a TT of 3 years for the 0–5 soil layer required an input similar in mass to the above lying organic horizon (13.6 Mg C ha^{-1} yr^{-1}), whereas a TT of 183 years required 0.22 Mg C ha^{-1}yr^{-1}, led us to assume 183 years as the most likely solution.

Results

All investigated sites show a soil bulk density of about 1 Mg m^{-3}, a sandy clay loam to loamy texture and an acidic pH, with no significant differences between sites ($p<0.05$) in fundamental soil properties (Table 1).

Changes in SOC concentration

Soil organic carbon concentration in the degraded forest is significantly lower than in the primary forest only in the 0-5 and 5-15 cm soil layers, whereas no significant differences are found in deeper layers (Table 2). Similarly to primary forest, cypress plantations show higher SOC concentrations than degraded forests in the uppermost soil layers. In deeper soil layers SOC concentrations is not significantly different between degraded forest and cypress plantations for any time since conversion, except for the oldest plantation (Table 2).

The SOC concentration in the 0-5 cm layer of the tea plantation 19 years after conversion (68.9±13.9 g C kg^{-1}) is significantly lower than that of the degraded forest (96.9±5.1 g C kg^{-1}). After 31 years of tea cultivation the SOC concentration increases significantly compared to the previous stage, 130.4±2.1 g C kg^{-1}, to remain stable even after 43 years of cultivation, 130.1±5.9 g C kg^{-1} (Table 2). In deeper layers the SOC concentration is significantly higher in the tea plantations than in the degraded forest, except in the youngest tea plantation (Table 2).

Changes in SOC stock

The organic horizon in the primary and degraded forests store similar amounts of C: 9.8±1.7 Mg C ha^{-1} and 8.7±1.8 Mg C ha^{-1}, respectively. The C stored in the organic horizon is significantly lower in the cypress plantations than the degraded forest along the whole chronosequence, 4.2±1.9 Mg C ha^{-1}, 5.1±1.9 Mg C ha^{-1} and 2.8±1.1 Mg C ha^{-1} after 19, 40 and 53 years since plantations establishment, respectively. Under tea, except for a significantly lower amount after 19 years, 2.5±1.3 Mg C ha^{-1}, the C stored in the organic horizon after 31 and 43 years following the establishment of the plantation is similar to that of the degraded forest: 10.5±2.1 and 9.0±1.9 Mg C ha^{-1}, respectively.

Differences in SOC concentration correspond to significant differences in SOC stocks, since the bulk density does not vary between sites (Table 1), and no rock fragments are present in these soils. Hence, the increases in SOC stocks can be entirely attributed to the increases in C concentration. Degraded and primary forests do not show significant SOC differences in the topsoil, due to the higher uncertainty resulting when considering the whole topsoil rather than the single layers comprised in this compartment (Figure 2). Analogously, the primary forest shows the same amount of SOC in the subsoil as the degraded forest, 193.8±20.8 and 193.1±17.0 Mg C ha^{-1}, respectively.

In the topsoil of the cypress chronosequence, the SOC stock increases linearly from the 148.4±7.8 Mg C ha^{-1} observed after 20 years since the plantations establishment to 185.5±8.0 Mg C ha^{-1} after 53 years (Figure 2). Considering the tea chronosequence, after 19 and 31 years no significant SOC difference is observed compared to the degraded forest. Nevertheless, the SOC stock increases with time to reach 169.6±9.7 Mg C ha^{-1} after 43 years since the plantations establishment. Changes occurring in the subsoil (30-100 cm) mirror that of the topsoil under both plantation types (Figure 2).

Changes in turnover time

The ^{14}C concentration decreases in all sites with increasing soil depth. Soil ^{14}C values of primary forest were higher than those of degraded forests (Table 3). In the cypress chronosequence, the ^{14}C concentration increases progressively from the degraded forest towards the oldest plantation (Table 3), for all the investigated layers. A similar trend is observed in the tea chronosequence, except for the 0-5 cm layer, where the ^{14}C concentration is higher than the degraded forest only in the oldest plantation (Table 3).

The differences in ^{14}C concentration result in clear differences in TT's. A longer TT is observed in all layers of the degraded forest compared with the primary forest (Table 4). The TT of the SOC in all investigated layers becomes shorter with increasing age of the cypress plantation (Table 4). In the tea chronosequence the trend is different, with a longer TT in the 0-5 cm layer of the 19-year-old (318 years) and 31-year-old tea plantations (238 years) but a shorter TT (102 years) in the oldest plantation. In the underlying two layers, the TT becomes shorter with increasing age of the plantation (Table 4).

Discussion

Effect of forest degradation on soil organic carbon levels

Our results indicate the presence of high SOC levels in the primary forest, in line with studies in both other forests blocks of the MFC and other primary forests in Kenya. Were et al. (2016) report for the Eastern part of the MFC an average SOC stock for the 0-30 cm layer of 110 Mg C ha^{-1} (Min = 75.5 Mg C ha^{-1} — Max = 142.9 Mg C ha^{-1}). Omoro et al. (2013) report for the mountain forests of the Taita Hills, in south-eastern Kenya, a SOC stock for the 0-50 cm depth of 305 Mg C ha^{-1}, much higher than the 185 Mg C ha^{-1} deriving from this study, while Glenday et al. (2006) report much lower values, 100 Mg C ha^{-1} for the 0-60 cm depth, for a primary forest in the Kakamega National Reserve, which is a tropical lowland forest. These contrasting results are probably related to altitude-driven, climatic differences of the sites. In addition, our results highlight the high SOC stock currently stored not only in the primary forest but also in the degraded forest. The SOC pool in tropical forests is known to undergo significant changes after conversion into other land uses and land covers (Don et al. 2011; Girmay et al. 2008), but little is known about response of the SOC pool to disturbances leading to forest degradation (Berenguer et al. 2014). In this study, forest degradation through illegal timber extraction implies a significant decline in the 0-5 cm and 5-15 cm layers of mineral soil, suggesting that the SOC pool is sensitive to forest degradation. However, we find no differences between the 0-30 cm layer of degraded and primary forests because the statistical significance observed in the top two layers is diluted when we calculate stocks across 0-30 cm depth. This is in line with a recent study in the tropical Amazonia (Berenguer et al. 2014), which showed no SOC differences in the 0-30 cm layer, comparing a large number of disturbed and undisturbed primary forests suggesting that the SOC pool is resistant to impacts of understory fires and selective logging. Our apparently contradicting results, depending on the soil depth under investigation, strongly suggest the need to evaluate the effect of a disturbance using narrower ranges of soil depths than using the usual 0-30 cm depth. Whereas the 0-30 cm topsoil layer is highly useful for standardized reporting purposes, it does not turn helpful for evaluating the effect of a soil disturbance.

In a global perspective, quantifying possible SOC losses from forest degradation become increasingly important to produce reliable C budgets, given the increasing forest area affected by degradation worldwide. The latest Forest Resource Assessment (FAO 2015b) reported a global figure on canopy cover reduction, defined as the loss of more than 20 percent of tree cover between 2000 and 2012, caused by forest degradation due to wood removals, fire and small clearances. In the tropics, the area subject to canopy cover reduction is 6.5 times that of deforested areas since 1990, and specifically for the African continent, forest degradation affect about 13 percent of the total forest area (Van Lierop et al. 2015).

SOC changes following cypress and tea plantations

The replacement of degraded forests with cypress and tea plantations within the MFC impact positively the SOC levels on the long term. The conversion to cypress plantations induces an almost linear SOC increases, and after 53 years, the SOC in the topsoil is about 50 Mg C ha^{-1} higher in the cypress plantation than in the degraded forest (Figure 2). Global meta-analyses suggest that the replacement of native forests by tree plantations generally reduce the SOC stock, particularly in the first decades, although conversion of native forest to plantations in tropical areas has no significant effect on SOC (Powers et al. 2011). In the available literature for the African continent, Glenday et al. (2006) did not observe significant changes between native forests and a 30-year-old cypress plantation in the Kakamega forest (western Kenya), in line with observations for the Taita Hills (south-eastern Kenya) considering a cypress plantation established from 30 years (Omoro et al. 2013). Nevertheless, higher SOC stocks in cypress plantations rather than native forests were already observed in East Africa (Lemma et al. 2006; Lamenih et al. 2004). From a meta-analysis study, Guo and Gifford (2002) concluded that 40 years might be needed before SOC stocks in conifer plantations return to the original levels of the indigenous forest they replaced. Our study shows that already after 20 years the SOC levels of the cypress plantations are not different from those of both degraded and primary forests and, more importantly, cypress plantations show the capacity to significantly exceed the SOC stocks of degraded forest after 40 years, and those of the primary forest after 53 years.

On the long term, large SOC increases are observed also for the tea plantations, but with a different temporal pattern. After 19 years since the establishment of the tea plantation, the SOC is similar to that of the degraded forest but lower compared to primary forest, while it significantly increases after 43 years of tea cultivation (Figure 2). These results are partially in contrast with the elsewhere-reported SOC decline, as a consequence of the conversion of primary forests to perennial tree cash crop plantations (see the tropical meta-analysis by Don et al. 2011, and Chiti et al. 2014). The relative SOC loss observed by these studies was about 30%. Van Straten et al. (2015) observed even larger SOC losses following the establishment of tree cash crop plantations in a pan tropical study, about half of the original SOC stock. Nevertheless, in China, Li et al. (2011) comparing the SOC stocks of tea plantations and primary forests did not observe significant differences.

The increases in SOC stock over time under both plantations could be mainly related to the fact that montane forests, which are rarely studied, have a reduced net primary productivity (NPP) compared to lowland tropical forests (Girardin et al. 2010). From a study along an altitudinal gradient in the Andes, Girardin et al. (2010; 2013) reported an NPP for primary forests located at 2000-2500 m a.s.l. of about 6-7 Mg C ha^{-1} yr^{-1}. For Cypress plantation the NPP can be around 8 Mg C ha^{-1} yr^{-1} (Liu et al. 2016), similarly to that observed for tea plantations at 2100 m of altitude in Kenya, about 6-8 Mg C ha^{-1} yr^{-1} (Magambo and Cannell 1981). A similar NPP imply a similar amount of C inputs to soil, suggesting that the observed differences in SOC stock are probably the result of a different quality of the C inputs.

The different trend in SOC accumulation observed in the topsoil of the two plantation types could be due to site preparation, which is more intense in the case of tea where the soil is prepared to favour drainage, possibly leading to high SOC losses (Wilsson and Clifford 1992). Using the approach described by Anderson-Teixeira et al. (2009), denominated as “free-intercept model”, it is possible to build a time-regression for the SOC stock in the topsoil for each chronosequence, to allow for the estimation of the SOC loss due to site preparation (time 0), calculated as the difference to the SOC in degraded forest. Upon this method, our results indicate a higher SOC loss due to the establishment of tea rather than of cypress plantations (28.8 Mg C ha^{-1} vs. 8.4 Mg C ha^{-1}, Figure 3). These different C losses can be confidently attributed to differences in site preparation, given the similarity of all the other external parameters, and contribute to explain the lower SOC concentration observed after 19 years of tea cultivation compared to degraded and primary forests.

It is worth noting that in the cypress plantations the SOC accrual takes place only in the topsoil, while in the subsoil no significant SOC increases are observed through the chronosequence, while under tea the SOC accruals in both the topsoil and subsoil. This different SOC distribution can be confidently attributed to the different roots system. While under Cypress roots are mainly concentrated in the 0-20 cm depth (Asaye and Zewdie 2013), under tea most of the roots are present within the 0-45 cm depth (Niranjana and Viswanath 2008) suggesting the importance of measuring SOC stocks and changes along the whole profile and not only in the superficial layers.

SOC stability along the chronosequences

The comparison of the TT’s indicates longer recycle times for the SOC in the different layers within the topsoil of the degraded forest rather than in the primary forest, suggesting that forest disturbance accelerates the decomposition of the more labile components of SOC. Labile SOC often consists of fresh plant residues and is physically protected from microbes within macro and micro-aggregates (von Lützow et al. 2006). Significant soil disturbance reduces the protection of labile SOC due to physical breakdown of soil aggregates (especially macro-aggregates) and enhanced oxygen diffusion into the soil matrix (Six et al. 2002). This interpretation is supported by the significant decreases in SOC concentration, and by the increases in TT, observed in both the 0-5 and 5-15 cm layers of the degraded forest. The faster cycling of the labile SOC pool following a disturbance, leaves the more stabilized, slow-turnover SOC pool as the dominant pool, resulting in higher TT (Wang et al. 1999). Contrarily, after the establishment of the plantations, the young and less stable

SOC starts to accumulate, due to the increased SOC protection by aggregates and the interaction with soil minerals (Six et al. 2002), contributing to decrease the TT with increasing age of the plantation, as reported recently by Chen et al. (2016). Similarly, to what we observed for the degraded forest, under tea the long TT observed in the 0-5 cm layer of the 19-year-old tea plantation can be related to the intense site preparation, which may have resulted in the preferential loss of labile C. Nevertheless, a reduction in TT is observable 31 years after the establishment of the tea plantation, suggesting that the effect of site preparation is diluted after this time span, in line with our results on SOC stocks.

Considering both the oldest plantations, the presence of the C produced with the nuclear weapon tests in the 1950's (bomb C) is clearly detectable down to 15 cm depth, indicating that most of the SOC stored in the topsoil, is derived from the cypress and tea vegetation present in those sites. Taking into account the SOC stock and the TT of the starting point (degraded forest) and the SOC stocks and TT's of the oldest plantations, it is possible to estimate the TT of the new SOC that was accumulated in the soil since establishment of the plantations. Considering the 0-5 cm layer, this result in a TT of 25 and 38 years for the cypress and tea plantations 53 years and 43 years since their establishment, respectively. The fast TT of the SOC that was accumulated in the mineral soil for the last 40-50 years greatly contribute to reduce the TT in the upper soil layers and is indicative of the small capacity of the investigated plantations to stabilize SOC when compared to primary forests.

Conclusions

The replacement of degraded forests with cypress and tea plantations stimulated a net SOC accrual in the uppermost 0-30 cm depth of the investigated soil, whose effect was clearly evident 30-40 years after forest replacement. Oppositely to the SOC decline usually observed following the establishment of tree cash crop plantations in lowland forests of Africa, our study shows the potential of tea for increasing SOC stocks on the long term. The SOC changes after conversion occurred mainly in the topsoil, although the significant changes observed in the subsoil of the tea plantations appeals for monitoring the SOC along the whole profile to accurately describe the SOC stock variations in case of interventions.

On the other hand, forest degradation resulted in a clear SOC decline in the top 15 cm of mineral soil suggesting that the effects of this type of disturbance has to be evaluated using a narrower range of sampling depths than usually done.

Policy makers should consider that whereas establishment of tree and tea plantations on degraded lands induces a long term substantial increase in the SOC pool, they undermine SOC stability, with unknown potential consequences of the replacement of primary or degraded forests with regard to SOC sequestration, especially in the frame of the ongoing alteration of environmental conditions.

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Figure captions

Figure 1 – Map of Kenya in the African continent (a) and map of the Mau forest complex with indicated the south-western part where all the plots are located (b). The square indicates the area where all sampling sites are comprised. Inset the position of the MFC in Kenya.

Figure 2 – Soil organic carbon stock in the topsoil (0-30 cm) and subsoil (30-100 cm) of the cypress (Figure 2a) and tea (Figure 2b) plantations. The vertical bars represent the standard error of the mean (n=10), while different letters indicate a significant difference (Tukey; $p<0.05$) within each soil compartment. PF=primary forest; DF=degraded forest, C=cypress, T=tea. Numbers close to site acronym represent the age of the plantation.

Figure 3 – Regression between the topsoil (0-30 cm) SOC stocks at different time to determine the SOC stock at year zero of the plantation for a) cypress and b) tea. The difference between the regression line at t=0 and the value of the degraded forest represents the SOC change due to vegetation removal and site preparation, assuming a linear SOC change after conversion.

Table 1 - Bulk density, particle size distribution and pH for the 0-30 cm depth of each site of the chronosequence (n=3 per site). Within each column, different letters indicate significant differences; no letters means no significant differences (Tukey test; p<0.05).

Vegetation	Time since deforestation	Bulk Density	Sand	Silt	Clay	pH
	yr^{-1}	$Mg\ m^{-3}$	$g\ kg^{-1}$	$g\ kg^{-1}$	$g\ kg^{-1}$	
Primary forest	n.a.	0.96±0.13	265±12	514±32	221±29	4.1±0.3a
Degraded forest	n.a.	0.99±0.15	224±20	548±28	228±31	4.3±0.2a
Cypress	20	1.04±0.12	282±28	521±18	197±28	4.6±0.2a
Cypress	40	1.12±0.18	246±32	533±22	221±43	4.7±0.3a
Cypress	53	1.09±0.17	273±22	512±25	215±27	4.5±0.2a
Tea	19	0.99±0.13	220±26	554±28	226±31	4.9±0.3b
Tea	31	0.97±0.18	247±29	499±33	254±28	4.7±0.2b
Tea	43	1.08±0.19	235±31	526±22	239±33	4.7±0.3a

Table 2 – Soil organic carbon concentration in the layers of the different plots of the two chronosequences (n=10 per layer). Within each column, different letters indicate significant differences (Tukey test; $p<0.05$). PF=primary forest; DF=degraded forest; C=cypress; T=tea Numbers close to site acronym indicate the time since the conversion.

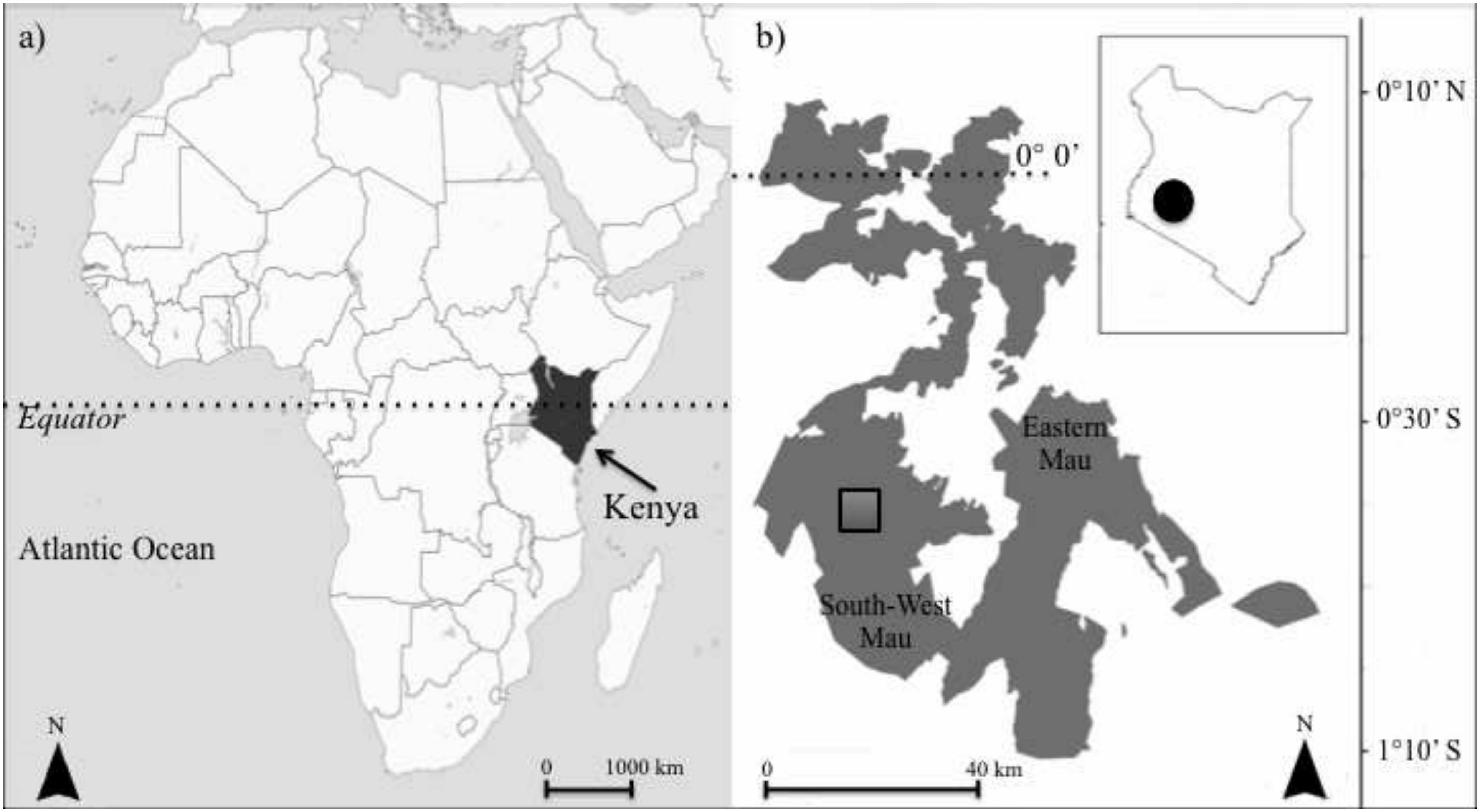
Site	Organic horizon	0-5 cm	5-15 cm	15-30 cm	30-50 cm	50-70 cm	70-100 cm
	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}
PF	412.3±23.2	118.5±7.9a	59.2±4.0a	40.0±2.9ac	31.6±2.1a	26.2±2.6a	22.5±3.6a
DF	408.2±21.3	96.9±5.1b	47.5±2.7b	34.4±4.2ab	30.2±3.8a	28.4±4.2a	23.0±3.5a
C 20	398.1±19.4	116.9±3.9a	46.9±2.0b	33.5±1.4b	33.5±1.9a	24.8±2.3a	22.4±1.2a
C 40	405.3±21.2	114.4±7.5a	66.7±3.8a	35.2±2.2ab	27.7±4.4b	26.1±4.9a	24.8±5.3ab
C 53	392.5±18.2	154.5±2.2c	62.9±1.5a	36.1±0.9ab	26.8±0.4b	25.7±1.1a	25.6±1.6b
T 19	388.5±17.3	68.9±13.9d	44.9±2.9b	39.2±0.7a	36.1±0.8c	28.8±1.4a	22.3±0.6a
T 31	375.1±18.1	130.4±2.1c	53.4±2.7a	42.3±2.0c	38.7±3.8cd	29.4±2.1a	26.8±1.7b
T 43	381.4±17.5	130.1±5.9c	50.8±2.9a	45.0±2.0c	41.5±3.5d	31.8±2.3a	28.5±0.9b

Table 3 - ^{14}C concentration values, expressed as pM carbon, and measurement uncertainty (σ) of the composite sample for each layer (n=10) from different sites. PF=primary forest; DF=degraded forest; C=cypress; T=tea. Numbers close to site acronym indicates the time since the conversion. Within each column, different letters indicate significant differences (t-test; $p<0.05$). Samples were collected in February 2013 and analysed in December 2013.

Site	0-5 cm		5-15 cm		15-30 cm	
	pMC %	σ	pMC %	σ	pMC %	σ
PF	104.6a	0.2	98.5a	0.2	92.7a	0.5
DF	103.9b	0.2	94.2b	0.4	86.5b	0.6
C 20	105.2c	0.2	94.5b	0.2	84.6c	0.2
C 40	108.3d	0.2	96.4c	0.3	85.2d	0.3
C 53	112.9e	0.2	98.4a	0.3	85.7d	0.4
T 19	100.9f	0.2	95.6d	0.2	91.0e	0.4
T 31	102.9b	0.4	98.3a	0.3	93.8f	0.4
T 43	109.0g	0.2	102.3e	0.2	94.1f	0.4

Table 4 - Turnover time of SOC for the different layers of each site. Numbers in brackets represent the TT that was discarded. PF=primary forest; DF=degraded forest; C=cypress; T=tea. Numbers close to site acronym indicates the time since the conversion.

Site	0-5 cm	5-15 cm	15-30 cm
	years	years	years
PF	186 ± 4 (3)	445 ± 12	867 ± 38
DF	209 ± 13	750 ± 45	1470 ± 54
C 20	174 ± 4 (4)	724 ± 15	1680 ± 16
C 40	112 ± 3 (11)	580 ± 20	1604 ± 29
C 53	56 ± 2 (20)	445 ± 8	1560 ± 37
T 19	318 ± 9	640 ± 17	1020 ± 35
T 31	238 ± 13	455 ± 28	770 ± 31
T 43	102 ± 3 (12)	260 ± 7	750 ± 28


a)
Equator
Kenya
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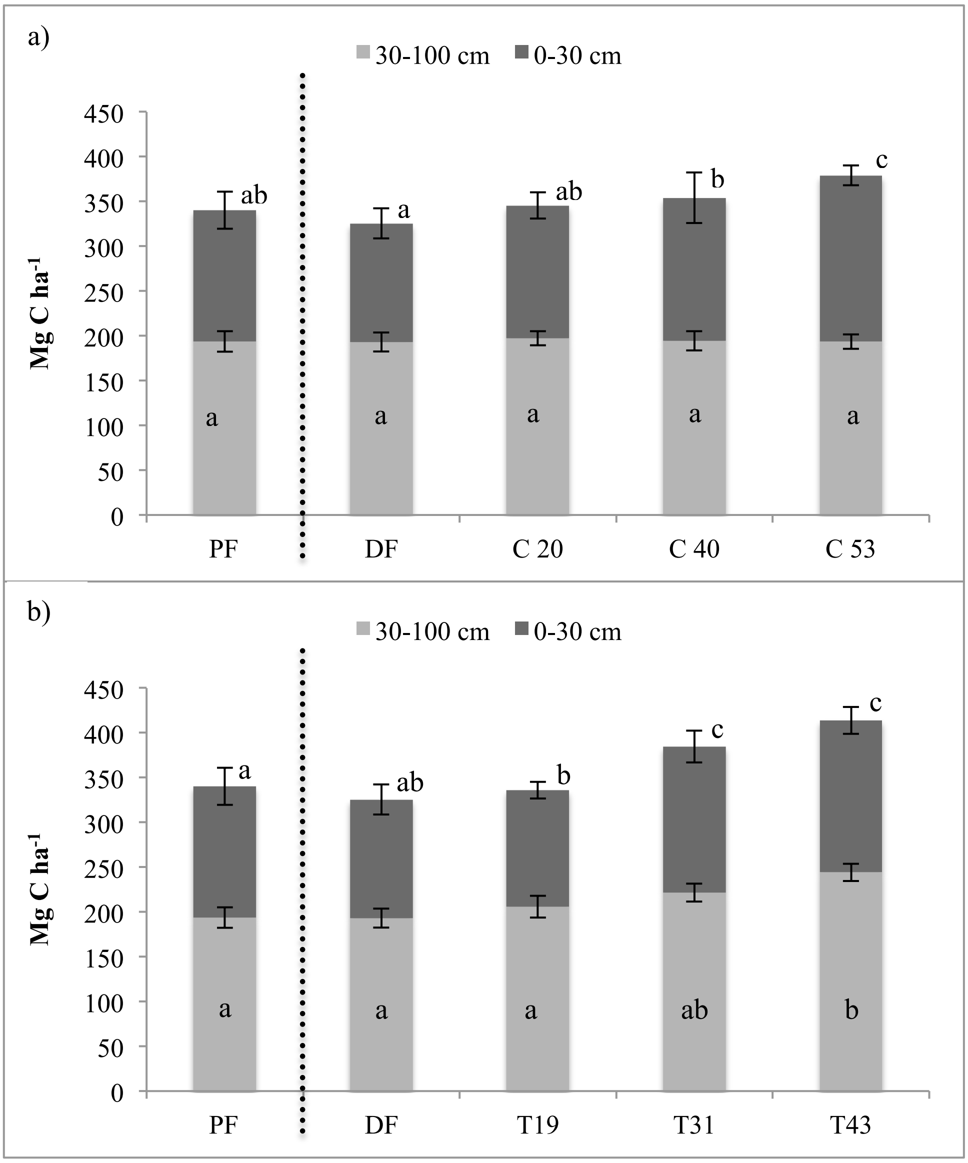
0°30' S
1°10' S


a)
30-100 cm
0-30 cm
Mg C ha^{-1}
450
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b)
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T19
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Figure 2 -

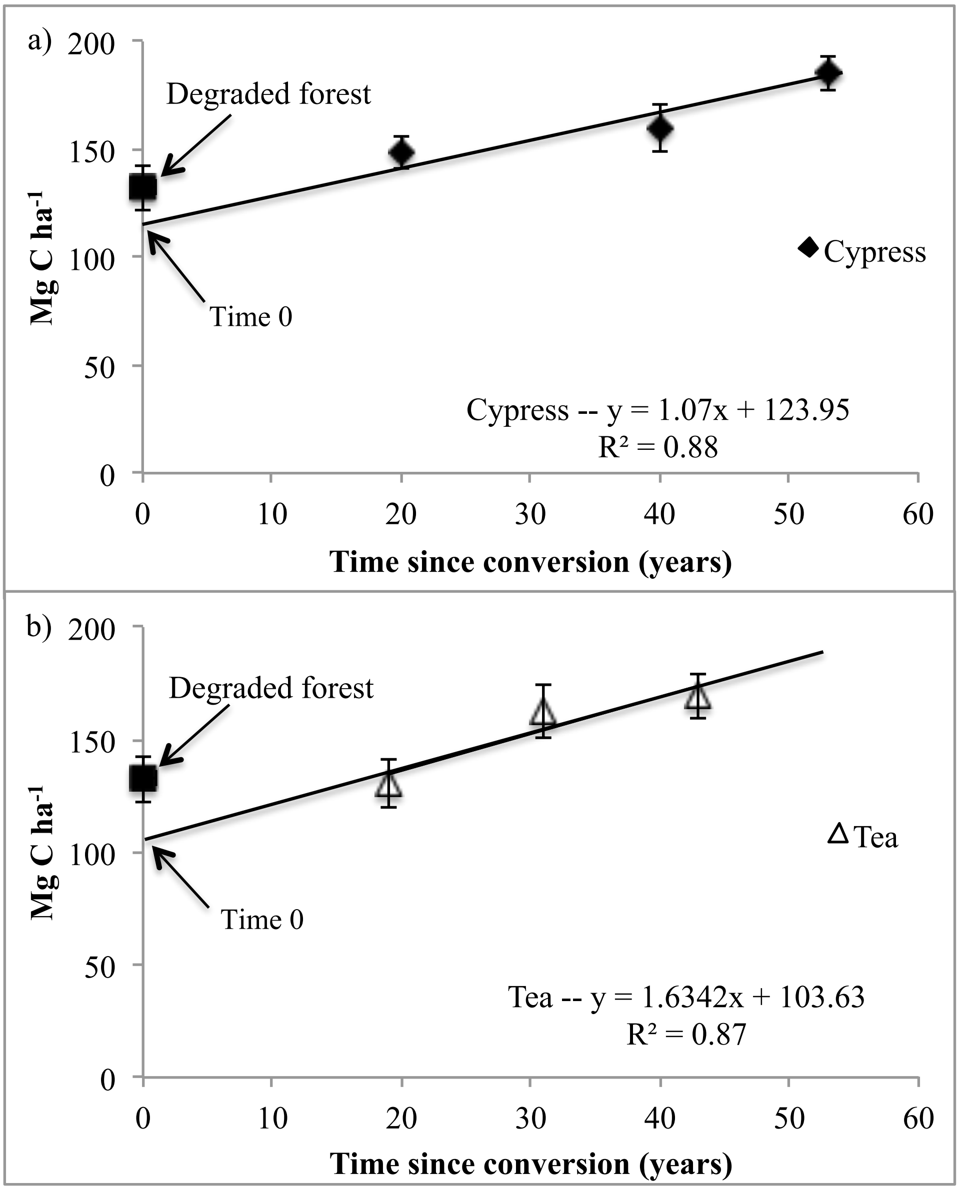
a)
200
150
100
50
0
Mg C ha^{-1}
Degraded forest
Time 0
◆Cypress
Cypress -- y = 1.07x + 123.95
R² = 0.88
0
10
20
30
40
50
60
Time since conversion (years)
b)
200
150
100
50
0
Mg C ha^{-1}
Degraded forest
Time 0
△Tea
Tea -- y = 1.6342x + 103.63
R² = 0.87
0
10
20
30
40
50
60
Time since conversion (years)

Figure 3 -