EFFECT OF TEA PLANTATION ON NUTRIENT STATUS OF OXISOLS IN AT THE TSHIVHASE ESTATE, LIMPOPO PROVINCE

BY

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Declaration

I, Ntsewa MR, declare that the mini-dissertation hereby submitted to the University of Limpopo, for the degree of Master of Science in Agriculture (Soil Science) has not previously been submitted previously by me for a degree at this or any other university; that it is my work in design and in execution, and that all materials contained herein have been duly acknowledged

NTSEWA MR____________	10 September 2021__
Ntsewa MR (Miss)	Date

Dedication

I dedicate this dissertation to my late father Mr Molatelo Thobakgale and mother Ms Martinah Ntsewa, my brothers Mr Vincent and Mr Peter Ntsewa and my sister Ms Mildred Ntsewa.

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Abstract

Addressing soil fertility decline and acidification due to land use change from undisturbed forest to tea plantation is important in order to foster sustainable management of tea plantations. The establishment of tea plantations could markedly lead to accumulation or depletion of carbon (C) and nutrients in soils. So far less is known on how the conversion of undisturbed forest to tea plantation influences the vertical distribution of soil C content and stocks in oxisols along a topographic gradient. The edaphic factors controlling the distribution of topsoil and subsoil C content and stocks in oxisols are poorly understood.

The objectives of this mini-dissertation were (1) to quantify and compare the vertical distribution of soil C content and stocks under tea plantation and undisturbed forest oxisols, and (2) to evaluate the edaphic factors controlling the vertical distribution of soil carbon and stocks under both land uses. In order to address these objectives, three topographical positions were selected (i.e. upslope, midslope and downslope) from the undisturbed forest (reference site) and adjacent the tea plantation. From each topographical position, three soil pits were dug to 100 cm soil depth. To determine the vertical distribution of C content and stocks, soil samples were collected from the 0-5 cm, 5-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm depth intervals. The soil samples were taken to the laboratory where they analysed for cha. Correlation analysis was carried out to determine relationships between soil carbon content and stocks as well as selected soil properties.

Results showed that soil C content and stocks were greater in tea plantation compared to undisturbed forest soils across all topographic positions. In both land uses carbon content and stocks declined with depth. Correlation analysis revealed that in the topsoil (0-40 cm), soil C was positively correlated with heavy metals; manganese ($r = 0.83$; $p<0.05$) and copper ($r = 0.69$), effective cation exchange capacity (ECEC) ($r=0.72$), mean weight diameter (MWD), a measure of soil aggregate stability ($r=0.73$) and negatively correlated with pH ($r = -0.51$). In the subsoil (40-100 cm), soil C was positively correlated with copper ($r = 0.92$) and zinc ($r = 0.86$), ECEC ($r = 0.69$) and MWD ($r = 0.48$) and negatively correlated with pH ($r = -0.57$) and clay ($r=-0.61$).

Furthermore, C stocks were positively correlated with acid saturation percentage ($r =0.50$) and negatively correlated with ECEC ($r = -0.59$), manganese ($r = -0.60$), exchangeable cations; potassium (r =- 0.56), calcium (r =-0.52) and magnesium (r = -0.65) in the topsoil. In the subsoil, C stocks are positively correlated with phosphorus (r = 0.79), potassium (r = 0.94), copper (r = 0.94), zinc (r =0.81) and MWD (r = 0.81) and negatively correlated with silt (r = -0.61), clay (r=-0.61), magnesium (r =- 0.50) and pH (r = -0.57). These findings suggest that soil C in both topsoil and subsoil of oxisols is chemically stabilized via complexation with polyvalent cations (heavy metals) and partly physically stabilized by soil aggregates.

Overall, the results show that land use change from undisturbed forest to tea plantation increased soil carbon content and stock in oxisols along a topographic gradient. Such information is important in understanding the behaviour of soil C content and stocks in tea plantation oxisols. Improved understanding of the effects of land use change from undisturbed forest to tea plantation, and how it influences soil C storage at varying topographic positions can help in development of sustainable tea plantation management practices that will mitigate soil fertility degradation.

Keywords: land use change, tea plantation, oxisols, vertical distribution, topography

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Tea (*Camellia sinensis*) is a perennial evergreen shrub that originates from China. *Camellia sinensis* is now grown in various parts of the world such as Africa, throughout Asia and some parts of the Middle East (Chopade *et al*., 2008). It can be cultivated in different environmental conditions ranging from temperate to humid regions as well as in areas with temperatures varying from 12-15°C (Dufresne and Farnworth, 2001). *Camellia sinensis* prefers soils under woodlands (areas with sparse 10-30% tree cover), but also thrives in well drained, deep, aerated, fertile acidic soils characterized by a pH between 4.5 and 5.6 (Bean, 1981; Huxley, 1992). Its agricultural productivity is affected by drought which can reduce yield by 14-20% (Cheruiyot *et al*., 2008). For instance, long periods of increased temperature have been reported to lead to yield losses (Hajiboland, 2017). Tea plants are harvested by plucking the young shots at regular intervals. The shoots plucked removes a certain amount of primary macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) from the plant-soil system (Tabu *et al*., 2015). Fertilization is used to supplement the nutrients removed by the shoots. Tea yields increase sharply with increased levels of fertilizers. Although high fertilization is required for high production, it leads to a decline in tea quality and high acidity resulting in physical and chemical soil degradation (Abe *et al*., 2006; Senapati *et al*., 1999).

Agriculture has been recorded to be one of the main causes of land use change in most parts of the world. Per year, 5.2 million ha is reserved for tea plantations, reforestation, and natural forest expansion (FAO, 2001). Tea plantation area covers approximately three million hectares of the world's arable land (FAO, 2007). In South Africa, tea plantation covers about 1 662 hectares of the country's arable land. It is grown in Limpopo (Tshivhase and Mukumbani tea estates), and Kwazulu-Natal (Ntingwe tea estate) provinces (DAFF, 2017). This study focuses on a 577 ha Tshivhase tea estate that has been growing tea for the past 30 years. The tea estate is sited on varying topography and oxisols, characterised by weak aggregate structure, high soil acidity, low soil fertility and high aluminium saturation (Fey, 2010). Land-use change from forest to tea plantations through long term cultivation may rapidly diminish soil quality (Desjardins *et al*., 2004). Studies by Reiners *et al*. (1994) and Van Noordwijk *et al*. (1997) have shown that land use change has an influence on soil physical and chemical properties. Moreover, it has a negative effect on soil organic carbon (SC) storage and soil nutrient availability (Templer *et al*., 2005). Important soil functions such as soil fertility and structure are dominantly controlled by SC in long term cultivations such as tea plantations. Land use changes from forest to tea plantations lead to spatial variability of SC stocks (Powers and Schlesinger, 2002). Understanding the factors leading to this variability is of importance for the development of management strategies that aim at improving soil functions.

1.2 Problem statement

In South Africa, tea plantation covers about 1 662 hectares of the country's arable land. It is grown in Limpopo (Tshivhase and Mukumbani tea estates), and Kwazulu-Natal (Ntingwe tea estate) provinces (DAFF, 2017). This study focuses on a 577 ha Tshivhase tea estate that has been growing tea for the past 30 years. The tea estate is sited on varying topography and oxisols, which characterised by weak aggregate structure, high soil acidity, low soil fertility and high aluminium saturation. Previous studies have shown that these soil conditions are limiting to tea production (Fageria and Baligar, 2008). In recent times, there has been a marked decline in tea quality at the estate. One of the possible mechanisms that could affect tea productivity (both quantity and quality) is soil acidification. The acidification of oxisols leads to different forms of soil degradation including chemical degradation that leads to loss of organic matter content, leaching of essential nutrients resulting in high levels of aluminium and low levels of exchangeable cations (Abe *et al*., 2006). Physical degradation through increase in soil surface compaction, erosion and reduced water holding capacity (Senapati *et al*., 1999), and biological degradation that lead to loss of important soil biota (Han *et al*., 2007). Overall degradation of soil results in increased aluminium mobilization, which in turn affects its accumulation in leaves, ultimately leading to poor quality of tea (Han *et al*., 2007; Alekseeva *et al*., 2011). Degradation of soil through acidification has been reported to decrease tea yield quality by 15% (Alekseeva *et al*., 2011).

1.3 Rationale

Addressing soil fertility decline and acidification due to land use change from undisturbed forest to tea plantation is important in order to foster sustainable management of tea plantations. Undisturbed forests are being converted to agricultural lands including tea plantation in response to the growing demands for food production (Ibechoubi and Yadava, 2017). Globally, an estimated 13 million hectares of forests are lost every year to agricultural lands. Land use changes from forests to tea plantations alters the soil physical and chemical properties, which in turn influence the fertility status and nutrient cycling (Neil *et al*., 1997). Disturbances of forests due to land use conversions lead to high organic N being transformed into inorganic N (NO_3^- and NH_4^+). For instance, a recent study by Ibechoubi and Yadava (2017) found that forest conversions into tea plantations led to a 1.3% and 2.56% increase in NO_3^- and NH_4^+ respectively. Ibechoubi and Yadava (2017), reported that organic nitrogen (N) is converted into inorganic N after forest disturbances such as clearing. Li *et al*. (2011) on the other hand found that tea plantations when compared to forests maintained a relatively higher C content in the topsoil layer (0-20 cm) of Acrisols due to the plant litter that decomposes on the surface after harvesting. Furthermore, the authors found that soil C decrease with depth. Zhou *et al*. (2000) corroborated these findings by showing that the total C storage in tea plantations (193.3 Mg C ha^{-1}) was higher than that of forests (187 Mg C ha^{-1}) due to higher biomass and plant litter.

Establishment of tea plantations could markedly change the pools of soil nutrients in oxisols (Cheruiyot *et al*., 2008). However, the effects of converting undisturbed forest to tea plantations along a topographic gradient on the vertical distribution of soil C content and stocks and associated degradation processes are poorly understood (Li *et al*., 2011). Improved understanding on the effects of land use change on soil carbon and nutrients stocks can help in the development of sustainable tea plantation management practices prudent in the restoration degraded soil.

1.4 Purpose of the study

1.4.1 Aim

The aim of the study is to investigate the long-term effect of tea plantation compared to undisturbed forest on the soil nutrient status of oxisols.

1.4.2 Objectives

The objectives of this study are:

i) to quantify and compare soil C content and stocks under tea plantation and undisturbed forest.
ii) to evaluate the edaphic factors influencing vertical distribution of C content and stocks under tea plantation and undisturbed forest.

1.4.3 Research questions

The project seeks to address the following research questions:

i) How does long-term (30 year) tea plantation affect the nutrient status of oxisols in Tshivhase Estate?
ii) What is the effect of topography on the vertical distribution of nutrients in oxisols under Tshivhase Estate tea plantation and undisturbed forest?

1.5 Mini – dissertation structure

This mini dissertation is arranged into four chapters. This chapter has provided the general introduction of this study. Chapter 2 provides a conceptual and pragmatic structure of the study by reviewing the literature on land use change, the long term effects of tea plantation on physical and chemical properties of soil and effect of topography on distribution of soil carbon. Chapter 3 explains the long term effects of tea plantation on nutrient status of oxisols (research question #1) and the effect of topography on the vertical distribution of nutrients in oxisols under tea plantation and undisturbed forest (research question #2). Chapter 3 also reports and discusses the findings of the research. The final chapter summarizes, concludes, recommends and suggests further areas of research that could be explored at a later stage.

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CHAPTER 2

LITERATURE REVIEW

2.1 Land use change from undisturbed forest to tea plantation

Globally, an estimated 13 million hectares of forests are lost every year. Undisturbed forests are being converted to agricultural lands including tea plantation in response to the growing demands for food production (Ibechoubi and Yadava, 2017). Tea plantation areas cover approximately three million hectares of the world's arable land (FAO, 2007). Forest cover has declined over the years while agricultural land use such as for tea plantations have increased (Yüksek *et al*., 2009).

Land use change influences the distribution and supply of soil nutrients to plants by directly altering soil properties. This is because conversion of forests to tea plantations leads to environmental challenges, including soil erosion, acidification and soil compaction (Salehi *et al*., 2008). Conversions from forest to tea plantations have been reported to decrease in soil organic in the short term (Murty *et al*., 2002) while in the long term tea plantations (30 years stand) result in an increase in SC (Li *et al*., 2011). The reduction of SC is due to the alteration of litter fall amount, litter chemistry and chemical and physical properties of the soil (Wang *et al*., 2013), which results in low soil productivity (Sanchez *et al*., 1997; Palm *et al*., 2001). Islam and Weil (2000) who conducted their study on oxisols in Bangladesh reported that conversion of forest to tea plantation increased soil bulk density and reduced porosity and aggregate stability. Such changes in the soil properties may subsequently result in soil degradation (Tukahirwa, 2003).

2.2 Soil degradation as a consequence of land use change

Soil degradation is both the physical loss (erosion) and the reduction of topsoil quality associated with soil fertility decline (Mupenzi *et al*., 2011). Soil degradation occurs when there is a decline in the productive or functional capacity of the soil because of adverse changes in biological, chemical, physical and hydrological properties (Gabriëls and Verdoodt, 2012). Yüksek and Kalay (2002) reported that converting alder forest to tea plantation degrades soil, where incidences of soil erosion were found to be higher just after the conversion to tea plantation. In tea plantations converted from forests, the soil protection ability against erosion is lower resulting in the topsoil being removed and eventually a change in soil structure (Yüksek *et al*., 2009). Yusek et al (2004) in Pazar, Turkey reported that the establishment of tea plantations after deforestation led to larger and frequent floods not only damaging plant life but also degrading soil properties observed similar results.

2.3 Effect of tea plantation on soil chemical properties

2.3.1 Effect of tea plantation on soil organic carbon (SC)

A study by Piao *et al*. (2009) in China showed that tea plantations had a higher C content than adjacent forests due to the degradation and overharvesting of forests. Four tea stands of 16 years, 23 years, 31 years and older than 50 years used in a study by Li *et al*. (2015) showed that tea plantation had a positive effect on soil properties and nutrients. In this study, SC increased with tea age until 31 years and slightly decreased thereafter. This shows that 16 and 23 year aged stands had better soil structure, thereby protecting SC. Long term tea plantation (more than 31 years) resulted in different forms of soil degradation including chemical degradation, that leads to loss of organic matter content, leaching of essential nutrients resulting in high levels of aluminium and low levels of exchangeable cations (Abe *et al*., 2006). Furthermore, long-term tea plantation led to physical degradation through increase in soil surface compaction, erosion and reduced water holding capacity (Senapati *et al*., 1999) as well as biological degradation through loss of important soil biota (Han *et al*., 2007).

Li *et al*. (2011), reported that tea plantations (16 years, 23 years, 31 years and greater than 50 years) age stands when compared to forests maintained a relatively higher C content in topsoil layer (0-20 cm) of Acrisols where 50% of C is accounted for due to decomposition of plant litter on the soil surface. The authors also revealed that SC decreased with depth. Zhou *et al*. (2000) corroborated these findings by showing that total C storage in tea plantations (193.3 Mg C ha^{-1}) was higher than that of forests (187 Mg C ha^{-1}) due to higher accumulation of biomass and plant litter. The source of SC in the topsoil studied (red yellow Podsols) was humus while in the subsoil inorganic calcium and magnesium carbonates played a key role. For each depth increment, SC levels under tea plantation decreased by 25% to 32% while SC in forest soils declined by 32% (Yüksek *et al*., 2009). The decline of SC was due to decreasing humus with increasing soil depth. These results were in contrast to a study by Gregorich *et al*. (1994) sited on chernozemic black soils who reported that immediately after the conversion of forests to tea plantation, SC is lost through mineralization and then followed by erosion which leads to SC depletion. This is in accordance with a study by Murty *et al*. (2002) who reported that conversion of forests to tea plantation resulted in a decrease in SC. Bahrami *et al*. (2010) also reported that the conversion of forests to tea plantation have brought about a decline of 34% in SC in forest soils and 23% in tea plantation soils. This decline was associated with a reduction in nutrient supply, water-holding capacity, aggregate stability and CEC in tea plantation soils (Bahrami *et al*., 2010).

2.3.2 Effect of tea plantation on soil pH

Soil acidification is a process whereby basic cations are leached and hydrogen ions increase in the soil. It is a natural process that can be accelerated by agricultural activities (Hou *et al*., 2015; Li *et al*., 2014). Following land conversion from undisturbed forest to tea plantation, the soil becomes strongly acidic. Soil acidity increases with increasing age stand of tea plantations (Ding and Haung, 1991). Apart from ammonium fertilizer, the other cause of soil acidity is high aluminium (Al), which is concentrated in plant litter. Tea plants are Al accumulators, whereby the Al is concentrated in the old tea leaves, and this is accelerated by the labile form of Al in acidic soils. The accumulation of Al in tea leaves results in biogeochemical cycling of Al during pruning thus increasing acidity (Han *et al*., 2007). Han *et al*. (2013) reported that the decomposition of plant litter could also be one of the causes of soil acidity through the decomposition process that releases organic acids that decrease soil pH.

A study by Alekseeva *et al* (2011) in the subtropical and temperate regions of China, conducted on Alfisols reported that a 17-year-old tea plantation decreased soil pH throughout the profile. This study reported that the rhizosphere soil (0-20 cm) had higher amounts of CEC, exchangeable Ca and K, and low amounts of exchangeable Al. These findings were in contrast with a study by Liu *et al* (2019) conducted on rhodic ferralsols who reported that exchangeable Al was high in the rhizosphere (0-10 cm) while acidification led to low amounts of exchangeable Ca and Mg.

Alekseeva *et al*. (2011) also reported that a 17-year-old tea plantation induced a decrease in soil pH up to 70 cm depth by at least 2.80 units. Furthermore, the authors reported that the decrease in soil pH lowered SC. This decrease in soil pH led to a decrease in exchangeable calcium (Ca^{2+}) and potassium (K^{+}), and an increase in exchangeable Al and H^{+} ions. Guicharnaud and Paton (2006), Pierson-Wickmann *et* *al*. (2009) and Starr and Lindroos (2006) also observed similar results. Studies by Mupenzi *et al*. (2011) in 11 different tea regions of Rwanda and Wang *et al*. (2010) across varying tea plantations stands (0, 13, 34, 54 years) in China sited on Alfisols reported that soil acidity decreased with depth due to the scarcity of high Al concentrated plant litter in the deeper layers (subsoil) of the soil, and also due to basic cation leaching into deeper depths, which neutralises the acidity.

2.3.3 Effect of tea plantation on exchangeable cations and CEC

A study by Islam and Sanullah (2011) in Chittagong Tea estate in Bangladesh showed that CEC varied with topographic positions with the highest observed in the midslope position of a 0-23 cm soil layer. Such variations were related to the type and amount of clay, pH and the organic matter present in the soil. A study by Alekseeva *et al*. (2011) reported that rhizospheres of tea plantations had more exchangeable Ca, K and high amounts of CEC. This was in line with a study by Chen *et al*. (2006) on Ultisols of two different tea experimental stations in the humid regions of Taiwan who also reported that rhizospheres contained high amounts of exchangeable Ca. The results obtained from the study were in contrast to a study by Bahrami *et al*. (2010) where four age stands (10, 20, 30 and 40 years) in the humid regions of Iran sited on red-yellow Podzolic soils showed that CEC decreased from 10.3 meq kg^{-1} in forest soils to 6.0 meq kg^{-1} in tea plantation soils. This decrease was due to low pH and SC in tea plantation soils (Martel *et al*., 1978). These results were similar to those of Tchienkoua and Zech (2004) who reported that the low values of exchangeable Ca and K observed in the topsoil were due to the nutrients being mined from this soil layer during harvesting. Mupenzi *et al*. (2001) also reported that exchangeable Ca was found to be at very low concentrations in tea plantations compared to undisturbed forests in the 0-40 cm soil layer. This was due to the low pH under tea plantation, which led to the leaching of this basic cation.

2.3.4 Effect of tea plantation on heavy metals

Soil acidification induced by long-term tea plantation (more than 30 years) leads to the activation of heavy metals such as lead (Pb), zinc (Zn), copper (Cu), chromium (Cr) and cadmium (Cd), thus increasing their accumulation in the soil and tea leaves (Zhang *et al*., 2006; Zhang and Fang, 2007). This acidification accelerates the rate of chemical weathering of soil minerals (Starr and Lindroos, 2006). Chemical weathering activates the depletion of CaO and the accumulation of SiO_2 and free Fe and Al oxides

(Alekseeva *et al*., 2011). Moderate amounts of Cu (a redox active metal) are required to promote plant growth. Soil acidity induced by land use change from forest to tea plantation led to high soil available Cu in the 0-30 cm layer where significant correlations between Cu and soil pH have been observed (Wang *et al*., 2008; Song *et al*., 2014). Chen *et al*. (2002) and Zeng *et al*. (2011) revealed that Zn, Fe and Mn are greatly depended on soil pH and a negative correlation was found between soil pH and the availability of Zn, Fe and Mn in oxisols. Liu *et al*. (2019) reported that Cu was correlated to SC, due to that it is bound to stable forms, and as such was not affected by the land use change from forest to tea plantation.

2.4 Effect of tea plantation on soil physical properties

2.4.1 Effect of tea plantation of soil bulk density

Soil bulk density is a measure of the degree of compaction in the soil. Illukpitiya *et al* (2004) reported that tea plantations in the mountain ecosystems of Sri Lanka had higher soil bulk density compared to adjacent undisturbed forest soils. On average, tea plantations increased soil bulk density by 47.3%. This is in accordance with a study by Xu *et al*. (2014) who also reported that non-ecological tea plantations in the tropical monsoon climate zone of China (Fujin Province) sited on yellow and yellow red soils had high soil bulk density leading to poor soil aeration and water permeability. Bahrami *et al*. (2010) reported that on average, tea plantations sited on red-yellow Podzolic soil led to a 75% increase in soil bulk density. Conforti *et al* (2016) also reported that across all topographic positions in the forests of southern Italy, soil bulk density increased with depth, and this was concurrent with studies by Illukpiya *et al*. (2004) and Yüksek *et al*. (2009). An increase in soil bulk density with depth was related to low soil organic matter down the soil profiles. SOM is one of the factors that influences soil bulk density. High SOM leads to low soil bulk density, therefore a decrease in SOM with depth causes an increase in soil bulk density (Illukpiya *et al*., 2004). One other possible factor that may lead to an increase of soil bulk density with depth is the weight of the overlying horizons (Gruneberg *et al*., 2014).

2.4.2 Effect of tea planation on aggregate stability

Le Bissonnais (1996) reported that high SOM leads to high aggregate stability. Generally, there is a positive correlation between SOM and aggregate stability (Chenu *et al*., 2000). A study conducted by Pierson and Mulla (1990) in the hot summer Mediterranean climate of Palouse, Washington under varying slope positions showed that soils in the downslope contained higher aggregate stability than upslope throughout the soil profile. In contrast, a study by Yüksek *et al*. (2009) in the humid Blacksea region in Turkey sited on red-yellow podsols showed that tea plantation had weak aggregate stability, with water stable aggregates (WSA) ranging from 64% to 69% in tea plantation soil and 66% to 71% in forests soils.

2.5 Effect of topography on the distribution of SC

At a local scale, SC is mostly influenced by parent material, soil properties and topography (Callesen *et al*., 2003). Topography controls the rate of redistribution of soil and has an effect on the rate of decomposition (Sariyildiz *et al*., 2005), stability between SC and topographic positions (Chaplot and Poesen, 2012) as well as the quality and quantity of SC (Yoo *et al*., 2005). Slope position of an area influences the microclimate, species composition and ecosystem function in many ecosystems (McNab, 1993; Sariyildiz *et al*., 2005). A study conducted by Xing *et al*. (2010) in Fujian Province, China under Typic Alliti-Udic Ferrosols showed that different slope positions had different impacts on nutrient content of the soil. Fissore *et al*. (2017), in a study in California in the Mediterranean climate sited on Calcic Haploxerolls reported that SC content was high in the downslope position compared to the upslope and midslope position, with low SC observed in the midslope. Low SC in midslope position was associated with high potential for erosion resulting in soil thinning. Conforti *et al*. (2016) also reported similar results. Fissore *et al*. (2017) further reported that SC at the downslope position is not necessarily stabilized on mineral surfaces, but simply protected from microbial decay through burial. Such results are similar to those of Lasanta *et al*. (2001) and Garcia-Ruiz, (2010) in the Mediterranean mountains. Pierson and Mulla (1990) reported that soils downslope contained higher SC than upslope. In contrast, a study by Khormalia *et al*. (2007) in Lahijan, Iran under humic conditions reported that SC was lower in downslope position. This was due to poor drainage conditions and lower vegetative growth, which resulted in low yield. Conforti *et al*. (2016) reported that soils on slope gradients of less than 17.6% have more SC than soils on steeper slopes. This is similar to results reported by Liu *et al*. (2006) and Wang *et al*. (2010) on different slope angles. The difference in SC with varying topographic positions could be due to the processes of erosion and deposition controlling soil and SC along topographic positions (Gregorich *et al*., 1998).

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CHAPTER 3

INFLUENCE OF LAND USE CHANGE FROM UNDISTURBED NATIVE FOREST TO TEA PLANTATION ON CARBON CONTENT AND STOCKS IN OXISOLS AT DIFFERENT TOPOGRAPHIC POSITIONS

Abstract

Land use conversion from undisturbed native forests to agricultural ecosystems affects the concentration and storage of carbon in the soil. Despite this, the factors controlling and the underlying mechanisms governing soil carbon stocks following land use change from native forests to tea plantations are less known, especially for highly weathered oxisols. To address this knowledge gap, this study quantified the vertical distribution of soil carbon content and stocks under 35-year-old tea plantation and compared it to an adjacent undisturbed native forest. In both land uses, soil carbon stocks were pooled and calculated for the topsoil (0-40 cm) and subsoil (40-100 cm) layers. Univariate analysis was applied to determine the factors controlling soil C in the topsoil versus subsoil. The vertical distribution graphs showed that soil carbon content and stocks were greater under tea plantation than in the undisturbed native forest. Correlation analysis identified effective cation exchange capacity and mean weight diameter as the most factors that controlled soil carbon in the topsoil. In the subsoil, soil C was positively correlated to heavy metals, nutrients and sand content and negatively correlated to pH. The relative importance of each of these factors differs under differing topographic conditions. These findings suggest that polyvalent cations exert a strong influence by chemically stabilising soil C in the in the topsoil, while in the subsoil, the C is soil aggregates physically protected by in both the topsoil and subsoil of the studied tea plantation oxisols.

Keywords: Oxisols, tea plantation, native forest, land use change, soil carbon stocks, topsoil, subsoil, topography

3.1 Introduction

Soil carbon stocks (SCS) are a key indicator of the sustainability of long-term agricultural productivity in agro-ecosystems (Bell *et al*., 2012). The stabilization of C in soil is important for improving soil fertility, which in turn enhances sustainable farming (Sarkar *et al*., 2018). Soil carbon is a key determinant of soil fertility through its positive effects on soil structure and soil chemical and biological properties which in turn stimulate primary production (Panakoulia *et al*., 2017). Land use changes from forest to cropland contribute towards the depletion of SCS (Jackson *et al*., 2017). The loss of SCS has a direct impact on land productivity and threatens the stability of agro-ecosystems because of a decline in soil fertility (Amundson *et al*., 2015; Machmuller *et al*., 2015). In some instances, the conversion of forests to croplands leads to environmental degradation and can be a major source of greenhouse gas emissions (Joshi *et al*., 2019). Preserving and increasing SCS in agroecosystems is vital for maintaining food security, mitigating soil degradation and climate change (Börjesson *et al*., 2018; Chenu *et al*., 2019; Mayer *et al*., 2019; Rüegg *et al*., 2019).

Land use change affects many of a soil’s key properties including organic matter, and its primary constituent soil C (Jobbágy and Jackson, 2000). Soil carbon stocks depend on the balance between soil C inputs from vegetation and outputs from mineralisation, erosion and leaching (Lorenz and Lal, 2018). The net C balance is altered by the conversion of natural ecosystems into intensive agricultural land (Guillaume *et al*., 2018). Land use defines the magnitude of C inputs into the soil through aboveground and belowground residues (Frasier *et al*., 2019). Specifically, changes in land use alters the balance between inputs and outputs leading to a alterations in both the soil C and its equilibrium as it re-adjusts to new levels of input and output (Gregory *et al*., 2016). Increasing aboveground biomass sequesters C from the atmosphere, but increases in biomass do not necessarily lead to immediate or long-term increases in soil C storage (Jackson *et al*., 2017). For instance, soils under tea plantation are subjected to pruning and most of the aboveground biomass is harvested, compared to soils under native undisturbed forest, which have no such disturbance and benefit from increased perennial inputs of C (Wiesmeier *et al*., 2012).

The regulation of soil carbon cycling is different in the subsoil compared to the topsoil (Salomé *et al*., 2010). To date, most research on the effect of agricultural management on soil C have focused on the topsoil (0-30 cm) and relatively little is known about C dynamics in the subsoil (Thorburn *et al*., 2012). Land use change affects soil C, but usually the topsoil only is considered (Gregory *et al*., 2016; Torres-Sallan *et al*., 2018).

Most studies of soil C in agricultural soil focus on the topsoil (to 30-cm depth) because it is the main zone of activity for crop roots (Gregory *et al*., 2016). Although considerable concentrations of soil carbon occur in the topsoil, there can be equal or greater total amounts in the subsoil (Jobbágy and Jackson, 2000; Gregory *et al*., 2014). Compared to topsoil, subsoil horizons may have a greater potential for C storage due to their generally higher clay mineral content, which potentially increases the protection of SOC against microbial decomposition (Torn *et al*., 1997; Baldock and Skjemstad, 2000). While the deeper mineral soil is assumed to be stable and largely insensitive to the effects of management activities, including deeper soil C in studies of soil C storage provides us with a more complete picture of soil C dynamics and the response of the whole soil to management activities (Diochon *et al*., 2009). Despite the large carbon stocks in the subsoil, they remain poorly understood and rarely measured (Jobbágy and Jackson. 2000; Jenkinson *et al*., 2008; Rumpel and Kögel-Knabner, 2011; Jackson *et al*., 2017). Deeper soils are often not monitored due to the effort involved in sampling (Hamburg *et al*., 2019). Predicting changes in soil C stocks of agricultural systems without accounting for changes in soil C in deeper soil layers can be problematic (Baker *et al*., 2007). Some soils tend to have a greater potential to sequester more C in the subsoil (Frasier *et al*., 2019). Changes in subsoil C content have been pointed out as a priority research area (Lorenz and Lal, 2005). Soil carbon is not only controlled by organic inputs from plants, but also depends strongly on soil type. Soil type that consists of mineralogy and texture is essentially ‘fixed’, whereas organic inputs can be manipulated by land use (Gregory *et al*., 2016). There is a need for better understanding of the processes and factors controlling C stabilization, especially after land use changes (Ghimire *et al*., 2017). Estimating belowground stocks of C is critical to understanding ecosystem responses to land use change (Vadeboncoeur *et al*., 2012).

Land use conversion from natural to agricultural ecosystems affects the concentration and storage of soil C depending on soil type (Zinn *et al*., 2005). Soil depth is a critical attribute of any soil, and determines rooting, moisture and nutrient storage, mineral reserve, anchorage and a range of conditions that affect plant growth (Yost and Hartemink, 2020). Less is known on how land use conversion from undisturbed native forests to tea plantations tea plantations influences carbon stocks at various soil depths.

In South Africa, some tea plantations are established on oxisols, which are highly weathered acid soils that are characterised by a sandy loam texture, with less clay in the topsoil than in the subsoil (Boul and Eswaran, 2000). Oxisols contain low quantities of essential macronutrients (Fey, 2010) and high amounts of sesquioxides (iron oxides and oxyhydrates) that influence their physical properties. The general acidic nature of oxisols results in low cation exchange capacity (CEC) and effective cation exchange capacity (ECEC). Due to the low CEC, these soils are unable to retain essential nutrients such as carbon and nitrogen in large quantities. Further, soil acidification and low soil fertility severely constrain agricultural production (Fageria and Baligar, 2008). The maintenance of soil carbon concentration at high levels is critical in oxisols because of its importance in soil fertility and cation exchange capacity. In fact, the management of oxisols essentially involves the management of SOM (Van Wambeke, 1992).

There is limited literature on the role of the edaphic factors in controlling soil carbon content and stocks in oxidic topsoil and subsoils that typically have low pH and CEC. The underlying mechanisms governing soil carbon content and stocks in oxisols following land use change from undisturbed forest to tea plantation remain elusive. The objectives of this study were (1) to quantify and compare the vertical distribution of soil carbon and stocks under tea plantation with undisturbed forest oxisols, and (2) to isolate and identify the controlling edaphic factors influencing the depth distribution of soil carbon and stocks under both land uses.

3.2 Methodology

3.2.1 Site description

The study site is located in the Tshivhase tea estate between in Vhembe district, South Africa (-22.93º N and 30.46º E). The Tshivhase tea estate is one of only two tea estates that remain operational and is still in production in the Vhembe region of the Limpopo Province, South Africa (DAFF, 2017). The mean annual precipitation in the area is 1700 mm, and the majority of the rainfall falls during the summer months of November to March. The mean annual temperature ranges from 14ºC to 24ºC. The area has an undulating topography with elevation ranging from 883 to 947 meters above sea level (m a.s.l.) and a mean slope gradient of 5%. The soils in the area have developed from weathered dolerite intrusions and are broadly classified as Hutton soil form (Soil Classification Working Group, 1991) or Oxisols (IUSS Working Group, 2014). The topsoil Orthic A horizons (0-40 cm) are underlain by red apedal B horizons. Fey (2010) reported that these soils are deep, well drained and highly suitable for agricultural production (Fey, 2010). The vegetation in the undisturbed native forest consists of *Ficus sycamorus*. The tea plantation is dominated by *Camelia sinensis L.*, a perennial evergreen shrub intensively managed for continuous growth of young shoots.

Prior to the present study, the site was a natural forest until 1976 when it was cultivated for tea production by a private company called Sapekoe-Pty Ltd. The tea plants have been grown in the estate for more than 40 years. In the 70s until 2008, the tea stands were fertilized organically using the leaf litter left behind from pruning. In 2009, an inorganic fertilizer was used for the year only and went back to organic fertilization. The tea stands are pruned in winter for a period of three months from May to July, then harvesting starts in September. Limpopo Department of Agriculture took over from Sapekoe-Pty Ltd in 2006 after the estate was shut down for two years. Prior 2004, the tea stands were irrigated using sprinklers and after 2006, the tea stands were rainfed.

Pruning has been practised for the last 35 years. Currently the tea plantation in the estate is managed without any fertilisation.

Figure 1: Map of the site showing location of undisturbed native forest and tea plantation at Tshivhase estate, Vhembe District, Limpopo Province, South Africa

3.2.2 Field sampling and soil sampling of the study area

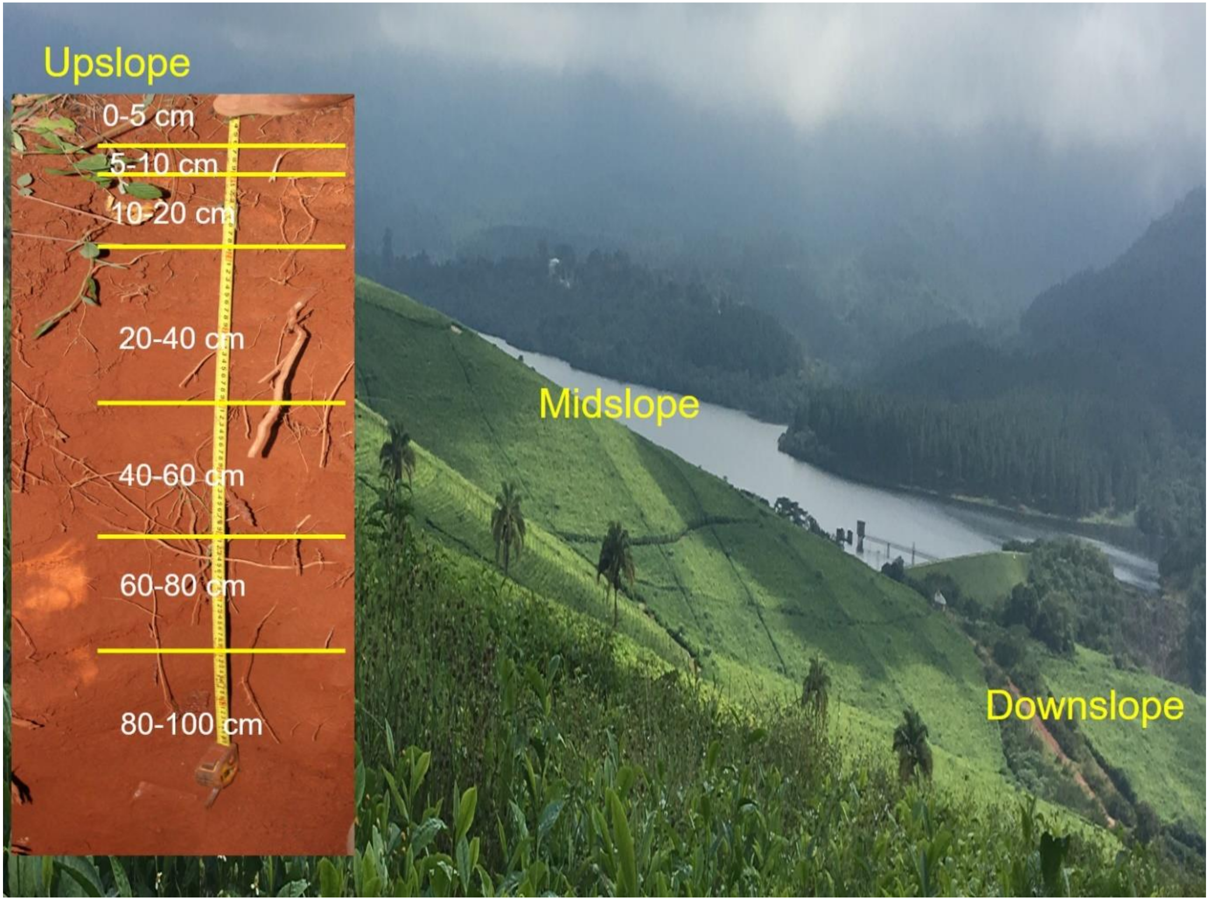

Figure 2: Photograph showing the topographic gradient of the tea plantation and the depth intervals from which soil samples were collected

In each of the tea plantation and undisturbed forest, three topographical positions were selected (i.e upslope, midslope and downslope) from the undisturbed forest and the tea plantation adjacent to it.

A field survey was conducted in 2018 in the tea plantation site and undisturbed forest (reference site). The reference site allowed us to define a stable equilibrium condition and true potential for carbon storage (Diochon *et al*., 2009). During selection of the sites, we ensured that they are adjacent to each other and have the same soil type, similar parent material, topography to minimise between site variability and limit potential obscurity from the land uses. During the survey, sampling locations were identified according to changes in topography in each land use. The hill slope morphology was used to subdivide sites into sampling sections (upslope, midslope, and downslope). At each topographic position, latitude and longitude coordinates and elevation were taken using a Garmin Etrex handheld GPS. The site characteristics and sampled locations are shown in Table 1 and Figure 1. At each topographic position, soil pits were dug to 100 cm depth, and each horizon was described following the Soil Classification Working Group, (1991). In each soil pit, three replicate 1 kg samples were collected from the 0-5 cm, 5-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm depth layers from each pit resulting in an overall total of 126 samples. Additional 378 core soil samples were collected to determine soil bulk density (Blake and Hartge, 1986). To achieve this, three replicated stainless steel cylindrical cores were pushed horizontally into the pit soil layers, thereafter removed and trimmed to remove the excess soil, retaining a ring volume of 238.9 cm^3. The collected samples were extruded into polythene sampling bags, sealed and stored in crates. The soil samples were returned to the laboratory at the University of Limpopo, where they were air-dried and ground to pass through a 2 mm sieve for physical and chemical analyses.

3.2.3 Soil physical analyses

3.2.3.1 Aggregate separation

In the laboratory, large soil aggregates were periodically broken down by hand along lines of weakness to obtain maximum millimeter-sized aggregates. Air-dried soil aggregates were separated by wet sieving through a series of three sieves to set apart four aggregate size fractions using the method described by Elliott (1986). The aggregate fractions were: i) >2000 µm (large macroaggregates), ii) 212-2000 µm (small macroaggregates), iii) 50-212 µm (microaggregates), and iv) <50 µm (silt and clay). An 80g sub-sample was spread on the 2000 µm sieve and then submerged in distilled water for 5 minutes, which resulted in slaking of the soil. The soil was sieved to separate water-stable aggregates by moving the sieve in an up-and-down motion with 50 repetitions over a period of 2 minutes. The soil material remaining on the 2000 µm sieve was backwashed into the beaker for drying. Soil and water that passed through the 2000 µm sieve were subjected to a smaller sized sieve whereby the sieving procedure was repeated, and this was done for all the sieve sizes. Aggregates that were separated were oven dried at 105˚C, weighed and stored at room temperature for analyses. Mean weight diameter (MWD), a measure of soil aggregate stability for each treatment was calculated using the following equation (Blaser *et al*., 2018):

$$MWD = (2*LM) + (1.106*sM) + (0.131*m) + (0.025*(s + c))$$

where LM represents the percentage of large macroaggregates, sM the percentage of small macroaggregates, m the percentage of microaggregates, and (s + c) the percentage of unaggregated silt and clay in each soil sample

3.2.3.2 Particle size distribution

A portion (25 g) of the samples was dispersed in sodium hexametaphostate and analysed for particle size distribution using the hydrometer method (Bouyoucos, 1962).

3.2.3.3 Soil bulk density

Soil bulk density samples were weighed, oven dried at 105ºC for 24 hours and then weighed again. The dry weight was then divided by the volume of the core. Bulk density (BD) was determined to calculate soil carbon stocks on the basis of the measured carbon concentration data. Bulk density was calculated as follows:

$$BD = \frac{M_D}{V}$$

Where BD is the soil bulk density (g cm^{-3}), M_D is mass of dry soil (g) and V is the volume of core (cm^{-3}).

3.2.4 Soil chemical analyses

Soils were analysed for total carbon by automated Dumas dry combustion using a Leco CNS 2000 analyser (LECO Corporation). Soil pH and EC were determined using Hanna Edge pH model HI763100 0-200 um/cm meter (Rhoades, 1982). Exchangeable Ca and Mg were extracted in 1M KCl, while K, P, Zn, Mn, and Cu were extracted in Ambic-2 extractant, containing 0.25M NH_4HCO_3 and determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (Perkin Elmer). Effective cation exchange capacity (ECEC) was calculated as the sum of KCl^-extractable Ca, Mg, acidity and extractable K. Percentage acid saturation of the ECEC was calculated as extractable acidity x 100/ (Ca^+ Mg^+ K^+ extractable acidity).

Calculation of soil carbon stocks

Soil carbon stocks in tea plantation and undisturbed forest were determined by multiplying the proportion of soil carbon by soil bulk density and depth increment using the following equation:

$$SC_S = \sum_{i=1}^{n} BD_i \times SC_i \times d_i$$

Where *BD* is the bulk density (g cm^{-3}), *SC* is total carbon content (kg m^{-2}) and *d* is the depth (cm).

3.3 Statistical analysis

Basic statistics of the data including minimum, maximum, average, median, standard deviation and coefficient of variation were computed in Excel following Webster (2001). Analysis of variance (ANOVA) was run to test the effect of land use, depth and topographic position on SCC, BD, and SCS. Statistical analysis was carried out with GenStat (18th Edition) (VSN International Ltd, Hemel Hempstead, UK). When any ANOVA effect was significant, the means were compared using Tukey’s test at 5% significance. Correlation matrix was performed ($p < 0.05$) on the dataset to isolate and identify edaphic factors controlling soil carbon content and stocks in the topsoil and subsoil of tea plantation and undisturbed forest using (STATISTICA 7.0). To visually display distribution of SCC and SCS, vertical distribution and box plot graphs were generated using SigmaPlot (Version 14, Systat Software Inc., CA, USA).

3.4 Results

3.4.1 Morphological and physicochemical characteristics of Oxisol profiles

Table 1 shows the morphological and physicochemical characteristics of the sampled oxisols situated at different topographic positions in the undisturbed native forest (reference site) and tea plantation. In the upslope position, the topsoil (Orthic A 0-40 cm) under the undisturbed forest was characterised by a reddish brown (2.5 YR4/4), sandy clay loam, particle size distribution of 22% clay, 16% silt, 62% sand; weak soil structure; high root distribution of 60%, a moderately acidic pH ranging from 4.18 to 4.43 and a clear smooth boundary. This layer was underlain by a red apedal B horizon (40 – 100 cm) characterised by a red (2.5YR 4/8) clay loam (28% clay, 21% silt, 50% sand); medium root distribution of 40% and a moderately acidic pH ranging from 4.33 to 4.84. The soil profile had an effective rooting depth of 100 cm.

In the midslope, the topsoil of the undisturbed forest was characterised by a reddish brown (2.5 YR4/4) sandy clay loam, with particle size distribution of 22% clay, 17% silt, 61% sand; weak structure; large roots distribution of 70%; a moderately acidic pH ranging from 4.20 to 4.27 and a gradual smooth boundary. This layer is underlain by a red apedal B horizon (40 – 100 cm) characterised by a reddish brown (2.5YR 4/4) clay loam (28% clay, 25% silt, 47% sand); large roots distribution of 30% and a moderately acidic pH ranging from 4.44 to 4.76. The profile as a whole had an effective rooting depth of 100 cm. In the downslope position, the topsoil of undisturbed forest was characterised by a reddish brown (2.5 YR4/4) sandy clay loam, with particle size distribution of 29% clay, 19% silt, 53% sand; weak structure; large roots distribution of 70%; a moderately acidic pH ranging from 4.01 to 4.09 and a gradual smooth boundary. This layer is underlain by a red apedal B horizon (40 – 100 cm) characterised by a red (2.5YR 4/8) clay loam (34% clay, 22% silt, 47% sand); large roots distribution of 30% and a moderately acidic pH ranging from 4.10 to 4.35. The profile as a whole had an effective rooting depth of 100 cm.

In tea plantation, the topsoil (Orthic A 0-40 cm) was characterised by a reddish brown (2.5 YR4/4), sandy clay loam, with particle size distribution of 22% clay, 21% silt, 58% sand; weak structure; medium roots distribution of 70%; a moderately acidic pH ranging from 3.92 to 4.18 and a clear smooth boundary. This layer is underlain by a red apedal B horizon (40 – 100 cm) characterised by a red (2.5YR 4/8) clay loam (32% clay, 27% silt, 41% sand); fine roots distribution of 70% and a moderately acidic pH ranging from 4.30 to 4.59. The profile as a whole had an effective rooting depth of 80 cm.

Under tea plantation, the topsoil (Orthic A 0-40 cm) was characterised by a reddish brown (2.5 YR4/4) sandy clay loam, with particle size distribution of 23% clay, 17% silt, 60% sand; weak structure; medium roots distribution of 60%; a moderately acidic pH ranging from 4.44 to 4.61 and a gradual smooth boundary. This layer is underlain by a red apedal B horizon (40 – 100 cm) characterised by a red (2.5YR 4/8) clay loam (28% clay, 22% silt, 50% sand); fine roots distribution of 40% and a moderately acidic pH ranging from 4.22 to 4.46. The profile as a whole had an effective rooting depth of 70 cm.

Under tea plantation, the topsoil (Orthic A 0-40 cm) was characterised by a reddish brown (2.5 YR4/4) sandy clay loam, with particle size distribution of 25% clay, 22% silt, 54% sand; weak structure; medium roots distribution of 60%; a moderately acidic pH ranging from 4.16 to 4.23 and a gradual smooth boundary. This layer is underlain by a red apedal B horizon (40 – 100 cm) characterised by a red (2.5YR 4/8) clay loam (35% clay, 26% silt, 39% sand); medium roots distribution of 40% and a moderately acidic pH ranging from 4.10 to 4.35. The profile as a whole had an effective rooting depth of 80 cm.

Table 1: Morphological characteristics of Oxisols sampled from undisturbed forest and tea plantation at different topographic positions

		Unisturbed Forest							Tea Plantation						
Slope position	Depth	Colour		Clay %	Silt %	Sand %	Textural class	pH	Colour		% Clay	% Silt	% Sand	Textural class	pH
Upslope	0-5	2.5YR4/4	Reddish brown	22	34	44	Sandy clay loam	3.92	2.5YR4/4	Reddish brown	21	10	69	Sandy clay loam	4.43
	5-10	2.5YR4/4	Reddish brown	22	15	64	Sandy clay loam	4.05	2.5YR4/4	Reddish brown	25	17	58	Sandy clay loam	4.29
	10-20	2.5YR4/4	Reddish brown	20	17	63	Sandy clay loam	4.15	2.5YR4/4	Reddish brown	18	19	63	Sandy loam	4.18
	20-40	2.5YR4/8	Red	22	19	59	Sandy clay loam	4.18	2.5YR4/4	Reddish brown	25	16	59	Sandy clay loam	4.18
	40-60	2.5YR4/8	Red	26	21	53	Sandy clay loam	4.30	2.5YR4/8	Red	24	17	59	Sandy clay loam	4.33
	60-80	2.5YR4/8	Red	33	30	37	Clay loam	4.58	2.5YR4/8	Red	29	23	48	Clay loam	4.41
	80-100	2.5YR4/8	Red	36	30	34	Clay loam	4.59	2.5YR4/8	Red	32	24	44	Clay loam	4.84
Midslope	0-5	2.5YR4/4	Reddish brown	22	17	61	Sandy clay loam	4.48	2.5YR4/4	Reddish brown	23	20	57	Sandy clay loam	4.27
	5-10	2.5YR4/4	Reddish brown	24	18	58	Sandy clay loam	4.44	2.5YR4/4	Reddish brown	20	17	63	Sandy loam	4.24
	10-20	2.5YR4/4	Reddish brown	23	16	61	Sandy clay loam	4.61	2.5YR4/4	Reddish brown	21	15	64	Sandy clay loam	4.20
	20-40	2.5YR4/4	Reddish brown	22	17	62	Sandy clay loam	4.57	2.5YR4/4	Reddish brown	24	17	59	Sandy clay loam	4.26
	40-60	2.5YR4/8	Red	22	15	63	Sandy clay loam	4.23	2.5YR4/4	Reddish brown	27	22	51	Sandy clay loam	4.44
	60-80	2.5YR4/8	Red	29	21	50	Clay loam	4.22	2.5YR4/4	Reddish brown	29	27	44	Sandy clay loam	4.64
	80-100	2.5YR4/8	Red	32	31	38	Clay loam	4.46	2.5YR4/4	Reddish brown	28	27	45	Sandy clay loam	4.76
Downslope	0-5	2.5YR4/4	Reddish brown	22	19	59	Sandy clay loam	4.17	2.5YR4/4	Reddish brown	24	17	59	Sandy clay loam	4.04
	5-10	2.5YR4/4	Reddish brown	19	17	64	Sandy loam	4.16	2.5YR4/4	Reddish brown	38	16	46	Clay loam	4.01
	10-20	2.5YR4/4	Reddish brown	25	24	51	Loam	4.19	2.5YR4/4	Reddish brown	25	19	56	Sandy clay loam	4.05
	20-40	2.5YR4/4	Reddish brown	32	26	42	Clay loam	4.23	2.5YR4/4	Reddish brown	28	22	50	Sandy clay loam	4.09
	40-60	2.5YR4/8	Red	36	25	39	Clay loam	4.34	2.5YR4/8	Red	30	27	43	Clay loam	4.10
	60-80	2.5YR4/8	Red	43	28	29	Clay	4.45	2.5YR4/8	Red	36	27	37	Clay loam	4.15
	80-100	2.5YR4/8	Red	26	24	50	Sandy clay loam	4.48	2.5YR4/8	Red	26	12	62	Sandy clay loam	4.35

3.4.2 Vertical distribution of soil carbon content, stocks and bulk density along topographic gradient

3.4.2.1 Vertical distribution of soil bulk density

In the upslope, there was an increase in soil bulk density from 0.86 to 0.97 g cm^{-3} in tea plantation in the topsoil (Orthic A 0-40 cm) compared to undisturbed forest which followed a similar trend (0.70 to 0.84 g cm^{-3}). In the subsoil (red apedal B 40-100 cm), the soil bulk density for both land uses further increased with depth where a greater increase was observed in tea plantation from 40 to 80 cm as compared to undisturbed forest.

In the midslope, the topsoil of oxidic soil (Orthic A 0-40 cm) was characterised by an increase in soil bulk density from the soil surface (0.80 g cm^{-3}) in tea plantation to 0.98 g cm^{-3} at the 40 cm layer while undisturbed forest showed a different trend where soil bulk density decreased from the soil surface (1.13 g cm^{-3}) to 1.03 g cm^{-3} at the 40 cm layer. In the subsoil (red apedal B 40-100 cm), the soil bulk density for tea plantation further increased with depth from 0.98 to 1.06 g cm^{-3} while soil bulk density for undisturbed forest continued to decrease until the 80 cm depth (0.97 g cm^{-3}) and then increased up to the 100 cm depth (1.05 g cm^{-3}).

In the downslope, there was an increase in soil bulk density from 0.71 to 0.87 g cm^{-3} in tea plantation in the topsoil (Orthic A 0-40 cm) compared to undisturbed forest which followed a similar trend (0.75 to 0.84 g cm^{-3}). In the subsoil (red apedal B 40-100 cm), the soil bulk density for both land uses further increased with depth from 0.87 to 1.02 g cm^{-3} and 0.84 to 0.99 g cm^{-3} in tea plantation and undisturbed forest respectively.

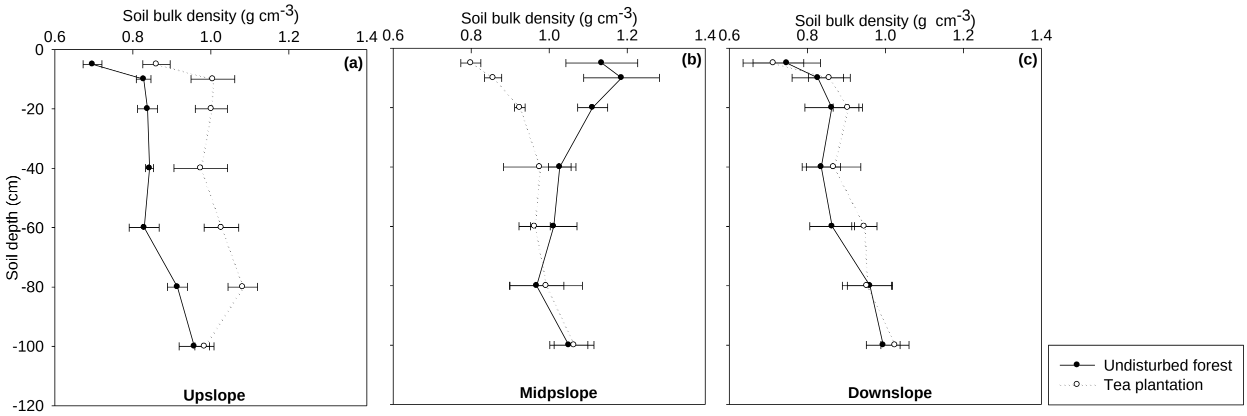

Figure 3: Vertical distribution of soil bulk density under undisturbed forest and tea plantation along the different topographic positions

3.4.2.2 Soil carbon content

Soil carbon content typically decreased from the topsoil to the subsoil (Figure 2) across all topographic positions. In the tea plantation, soil carbon content decreased from 53.40 g kg^{-1} to 30.67 g kg^{-1} in the 0- 40 cm layer compared to undisturbed forest which followed a similar trend where the total carbon content decreased from 69.40 g kg^{-1} to 37.16 g kg^{-1}.

In the upslope, the topsoil (Orthic A 0-40 cm) was characterised by SCC from the soil surface in both land uses (tea plantation and undisturbed forest). In the subsoil (Red apedal B 40-100 cm), the total carbon content for both land uses is decreasing with a smaller decrease observed in tea plantation (16.90 g kg^{-1}) as compared to undisturbed forest (6.85 g kg^{-1}).

In the midslope, the topsoil was characterised by decreasing total carbon content from the soil surface (50.27 g kg^{-1}) in tea plantation to 26.33 g kg^{-1} at the 40 cm layer while undisturbed forest showed a different trend where there was a decrease of total carbon content from the surface followed by an increase from the 10 cm layer (20.03 g kg^{-1}) to the 20 cm layer (27.20 g kg^{-1}) then decreased until the 40 cm depth (21.30 g kg^{-1}). In the subsoil (Red apedal B 40-100 cm), the total carbon content for tea plantation and undisturbed forest from 26.33 to 13.63 g kg^{-1} and 21.30 to 12.51 g kg^{-1} respectively.

In the downslope, the topsoil of oxidic soil (Orthic A 0-40 cm) was characterised by decreasing total carbon content from the soil surface in both land uses (tea plantation and undisturbed forest). Tea plantation had 58.20 g kg^{-1} carbon content at the soil surface then decreased to 28.30 g kg^{-1} at the 40 cm layer compared to undisturbed forest that followed a similar trend where the total carbon content decreased from 60.47 g kg^{-1} to 13.90 g kg^{-1}. In the subsoil (red apedal B 40-100 cm), the total carbon content for both land uses further decreased with a smaller decrease observed in tea plantation (10.40 g kg^{-1}) as compared to undisturbed forest (6.31 g kg^{-1}).

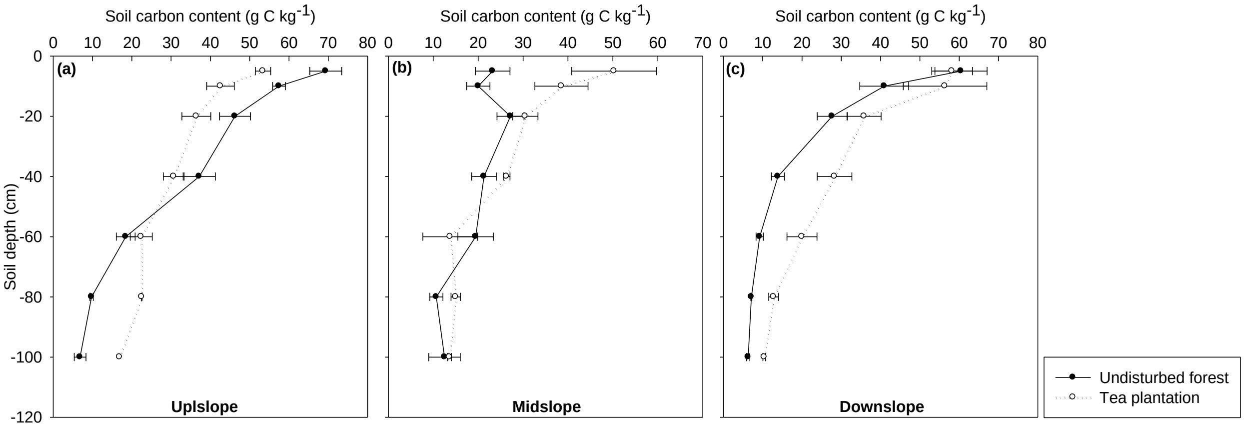

Figure 4: Vertical distribution of soil carbon content under undisturbed forest and tea plantation along the different topographic positions.

3.4.2.3 Vertical distribution of soil carbon stocks

In the upslope, there was an increase in soil carbon stock from 2.29 to 6.04 kg m^{-2} in tea plantation in the topsoil (Orthic A 0-40 cm) compared to undisturbed forest which followed a similar trend (from 2.42 to 6.25 kg m^{-2}). The highest value of stock was observed at the 40 cm depth for both land uses. The stock then decreased with depth in the subsoil (red apedal B 40-100 cm) with greater decrease observed in the undisturbed forest (1.30 kg m^{-2}) as compared to the tea plantation (3.32 kg m^{-2}).

In the midslope, the soil carbon stocks increased from the soil surface where tea plantation had more stocks (2.00 kg m^{-2}) than undisturbed forest (1.28 kg m^{-2}) in the topsoil (Orthic A 0-40 cm). More soil carbon stocks were observed in tea plantation (5.14 kg m^{-2}) as compared to undisturbed forest (4.39 kg m^{-2}) at the 40 cm layer. The stocks then decreased with depth in the subsoil (red apedal B 40-100 cm) to 2.89 and 2.66 kg m^{-2} in tea plantation and undisturbed forest respectively.

In the downslope, there was an increase in soil carbon stocks across both land uses (tea plantation and undisturbed forest) where tea plantation had more stocks as compared to undisturbed forest in the topsoil (Orthic A 0-40 cm). Soil carbon stocks in tea plantation increased until the depth of 40 cm with stocks being the highest at that depth (4.92 kg m^{-2}). Soil carbon stocks in undisturbed forest increased with depth until the 20 cm layer (2.42 kg m^{-2}) from which the stocks become constant until the 40 cm layer. The stocks for both land uses then decreased with depth in the subsoil (red apedal B 40-100 cm) with greater decrease observed in undisturbed forest (1.26 kg m^{-2}) as compared to tea plantation (2.14 kg m^{-2}).

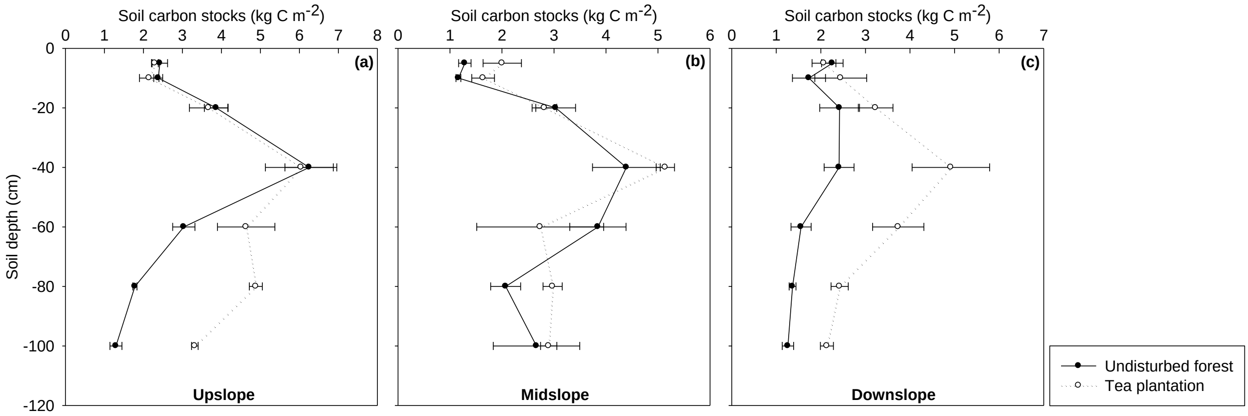

Figure 5: Vertical distribution of soil carbon stocks under undisturbed forest and tea plantation along the different topographic positions.

Table 2: Pearson correlation coefficients between soil carbon content and stocks with selected soil properties in the topsoil of tea plantation and undisturbed forest Oxisol. Significant correlations are highlighted in bold (P ≤ 0.05)

Upslope	BD	TC	SCs	Clay	Silt	Sand	P	K	Ca	Mg	Exch. A	T cations	Acid-sat	pH(KCl)	Zn	Mn	Cu	MWD
BD	1.00																	
TC	**-0.62**	1.00																
SCs	0.28	**-0.51**	1.00															
Clay	0.26	0.00	0.20	1.00														
Silt	**-0.46**	0.21	-0.20	-0.08	1.00													
Sand	0.32	-0.19	0.10	-0.36	**-0.90**	1.00												
P	**0.55**	-0.04	-0.15	-0.07	-0.10	0.13	1.00											
K	-0.08	0.39	**-0.56**	0.03	-0.21	0.18	0.36	1.00										
Ca	0.15	0.18	**-0.52**	0.05	-0.23	0.20	**0.44**	**0.78**	1.00									
Mg	0.08	0.12	**-0.46**	-0.02	-0.30	0.29	0.27	**0.73**	**0.89**	1.00								
Exch. A	**-0.46**	**0.58**	0.05	0.07	**0.46**	**-0.46**	-0.19	-0.32	**-0.56**	**-0.60**	1.00							
T cations	-0.24	**0.72**	**-0.59**	0.10	0.08	-0.12	0.32	**0.69**	**0.72**	**0.63**	0.16	1.00						
Acid-sat	-0.26	0.04	**0.49**	0.00	0.24	-0.23	**-0.43**	**-0.69**	**-0.94**	**-0.90**	**0.73**	**-0.52**	1.00					
pH	0.33	**-0.51**	-0.13	-0.08	**-0.42**	**0.43**	0.10	0.37	**0.62**	**0.71**	**-0.94**	-0.01	**-0.76**	1.00				
Zn	0.31	0.24	**-0.43**	0.16	-0.30	0.21	**0.53**	**0.71**	**0.79**	**0.72**	-0.35	**0.66**	**-0.72**	0.38	1.00			
Mn	**-0.70**	**0.83**	-0.35	-0.01	**0.59**	**-0.55**	-0.09	0.08	-0.03	-0.11	**0.75**	**0.58**	0.23	**-0.67**	-0.01	1.00		
Cu	**0.52**	-0.05	-0.20	0.25	-0.24	0.12	**0.46**	0.33	0.32	0.33	-0.07	0.34	-0.35	0.11	**0.50**	-0.16	1.00	
MWD	0.28	0.18	-0.11	0.27	**-0.41**	0.26	0.31	**0.57**	**0.47**	**0.45**	-0.14	**0.46**	-0.34	0.22	**0.59**	-0.12	**0.52**	1.00
Midslope																		
BD	1.00																	
TC	**-0.72**	1.00																
SCs	-0.09	-0.04	1.00															
Clay	0.35	-0.39	-0.04	1.00														
Silt	0.23	-0.06	-0.11	0.30	1.00													
Sand	-0.35	0.25	0.10	**-0.75**	**-0.86**	1.00												
P	**-0.56**	**0.65**	-0.11	0.24	-0.08	-0.07	1.00											
K	-0.38	**0.59**	**-0.50**	0.03	0.22	-0.17	**0.63**	1.00										
Ca	**0.46**	-0.28	-0.30	-0.13	-0.10	0.14	-0.26	-0.19	1.00									
Mg	0.38	-0.17	**-0.65**	0.07	0.13	-0.13	0.00	0.15	**0.66**	1.00								
Exch. A	**-0.51**	0.39	0.19	0.03	-0.06	0.03	**0.44**	0.33	**-0.84**	**-0.62**	1.00							
T cations	0.38	-0.16	**-0.45**	-0.13	-0.11	0.14	-0.07	0.01	**0.95**	**0.75**	**-0.67**	1.00						
Acid-sat	**-0.44**	0.23	**0.44**	0.03	-0.06	0.03	0.22	0.07	**-0.90**	**-0.81**	**0.91**	**-0.83**	1.00					
pH	**0.43**	-0.30	-0.01	-0.10	-0.14	0.15	-0.33	**-0.43**	**0.86**	0.30	**-0.80**	**0.70**	**-0.69**	1.00				
Zn	**0.57**	-0.27	-0.04	0.22	0.27	-0.31	-0.20	-0.09	0.22	0.37	-0.14	0.28	-0.29	0.01	1.00			
Mn	0.27	0.01	**-0.60**	0.16	0.17	-0.21	0.20	0.39	**0.43**	**0.87**	-0.33	**0.59**	**-0.62**	-0.03	**0.48**	1.00		
Cu	**-0.76**	**0.45**	0.07	-0.22	-0.17	0.24	0.38	0.20	**-0.68**	**-0.45**	**0.67**	**-0.59**	**0.70**	**-0.60**	**-0.53**	-0.39	1.00	
MWD	**-0.84**	**0.73**	0.00	**-0.48**	-0.08	0.31	**0.44**	**0.56**	**-0.43**	-0.40	**0.49**	-0.35	0.40	**-0.41**	**-0.42**	-0.28	**0.61**	1.00
Downslope																		
BD	1.00																	
TC	-0.22	1.00																
SCs	**0.50**	-0.04	1.00															
Clay	0.22	-0.10	0.00	1.00														
Silt	0.19	-0.31	0.11	0.26	1.00													
Sand	-0.25	0.26	-0.07	**-0.79**	**-0.80**	1.00												
P	-0.21	**0.49**	-0.10	0.18	**-0.64**	0.29	1.00											
K	-0.21	**0.46**	0.04	0.06	**-0.42**	0.23	**0.65**	1.00										
Ca	-0.21	**0.59**	-0.23	-0.24	-0.04	0.17	-0.04	0.00	1.00									
Mg	-0.28	0.38	-0.34	-0.29	0.01	0.17	-0.26	-0.26	**0.90**	1.00								
Exch. A	0.36	0.19	0.35	0.38	-0.06	-0.20	0.27	**0.45**	**-0.46**	**-0.57**	1.00							
T cations	-0.12	**0.72**	-0.15	-0.13	-0.07	0.13	0.02	0.15	**0.93**	**0.82**	-0.12	1.00						
Acid-sat	0.34	-0.38	**0.50**	0.39	0.10	-0.31	0.06	0.18	**-0.85**	**-0.85**	**0.73**	**-0.66**	1.00					
pH	0.01	**-0.45**	-0.31	-0.08	**0.51**	-0.27	**-0.72**	**-0.66**	0.31	**0.51**	**-0.68**	0.11	**-0.45**	1.00				
Zn	-0.11	0.29	0.33	-0.33	-0.26	0.37	-0.06	0.30	0.20	0.17	0.15	0.30	-0.03	-0.09	1.00			
Mn	**-0.43**	**0.62**	-0.35	-0.07	-0.35	0.26	**0.58**	**0.50**	**0.42**	0.19	-0.16	0.36	**0.49**	-0.29	-0.04	1.00		
Cu	-0.01	**0.69**	-0.16	-0.34	**-0.45**	**0.50**	0.30	0.32	**0.47**	0.34	0.21	**0.61**	-0.30	-0.30	0.36	0.20	1.00	
MWD	-0.09	**0.72**	-0.01	-0.19	-0.26	0.28	**0.47**	0.34	**0.52**	0.28	0.09	**0.58**	**-0.42**	-0.40	0.06	**0.54**	**0.47**	1.00

TC, total carbon; BD, soil bulk density; SCs, soil carbon stocks; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Exch. A, exchangeable acidity; T cations, total cations; Acid sat., acid saturation percentage; Zn, zinc; Mn, manganese; Cu, copper; MWD, mean weight diameter

3.4.3 Correlation between soil carbon content and stocks with soil properties in the topsoil and subsoil

Overall, soil carbon content in the topsoil (0-40cm) under tea plantation was 20–40% higher compared to undisturbed forest (Figure 5).

A correlation matrix of the data was run to determine the factors controlling soil C content and stocks in the topsoil and subsoil at different topographic positions (Table 2). In the upslope position, the correlation analysis indicated that C content in topsoil was positively correlated with manganese ($r = 0.83$: $p < 0.05$), effective cation exchange capacity ($r = 0.72$) exchangeable acidity ($r = 0.58$) and negatively correlated with and pH ($r = -0.51$). The soil carbon stocks were positively correlated with acid saturation percentage ($r = 0.49$ and negatively correlated with effective cation exchange capacity ($r = -0.59$), potassium ($r = -0.56$), calcium ($r = -0.52$), magnesium ($r = -0.46$) and zinc ($r = -0.43$).

In the midslope position, soil C content was positively correlated with mean weight diameter ($r = 0.73$), phosphorus ($r = 0.65$), potassium ($r = 0.59$), and copper ($r = 0.45$). The soil carbon stocks were positively correlated to acid saturation percentage ($r = 0.44$) and negatively correlated to magnesium ($r = -0.65$), manganese ($r = -0.60$) and potassium ($r = -0.50$).

In the downslope position, soil carbon content was positively correlated with mean weight diameter ($r = 0.72$), effective cation exchange capacity ($r = 0.72$), copper ($r = 0.69$), manganese ($r = 0.62$), calcium ($r = 0.59$), phosphorus ($r = 0.49$), potassium ($r = 0.46$), and negatively correlated with pH ($r = -0.45$). Soil carbon stocks were only positively correlated to acid saturation percentage ($r = 0.50$).

Table 3: Pearson correlation coefficients between soil carbon content and stocks with selected soil properties in the subsoils of tea plantation and undisturbed forest Oxisol. Significant correlations are highlighted in bold (P ≤ 0.05)

Upslope	BD	TC	SCs	Clay	Silt	Sand	P	K	Ca	Mg	Exch. A	T cations	Acid-sat	pH (KCl)	Zn	Mn	Cu	MWD
BD	1.00																	
TC	0.32	1.00																
SCs	**0.55**	**0.96**	1.00															
Clay	-0.27	**-0.61**	**-0.61**	1.00														
Silt	-0.36	**-0.60**	**-0.61**	**0.79**	1.00													
Sand	0.33	**0.63**	**0.65**	**-0.95**	**-0.95**	1.00												
P	**0.48**	**0.74**	**0.79**	**-0.60**	**-0.55**	**0.61**	1.00											
K	**-0.47**	0.05	-0.07	-0.19	-0.17	0.19	0.16	1.00										
Ca	0.17	0.14	0.16	0.31	0.23	-0.29	0.02	-0.41	1.00									
Mg	0.05	-0.15	-0.11	0.37	0.36	-0.39	-0.13	-0.25	**0.81**	1.00								
Exch. Acidity	0.15	**0.49**	**0.48**	**-0.56**	-0.45	**0.53**	**0.74**	**0.48**	**-0.50**	**-0.52**	1.00							
T cations	0.28	**0.56**	**0.57**	-0.22	-0.17	0.21	**0.73**	0.12	**0.50**	0.39	**0.48**	1.00						
Acid-sat	-0.08	0.16	0.12	-0.45	-0.35	0.42	0.38	**0.53**	**-0.75**	**-0.79**	**0.83**	0.04	1.00					
pH	-0.16	-0.42	-0.41	**0.65**	**0.51**	**-0.61**	**-0.54**	-0.34	**0.69**	**0.82**	**-0.84**	-0.08	**-0.91**	1.00				
Zn	-0.23	-0.46	-0.44	0.22	0.27	-0.26	-0.23	0.04	-0.20	0.17	-0.18	-0.28	-0.11	0.31	1.00			
Mn	**-0.73**	-0.17	-0.35	-0.05	0.05	0.00	-0.11	**0.72**	**-0.55**	-0.42	0.40	-0.12	**0.65**	-0.42	0.12	1.00		
Cu	**0.48**	**0.92**	**0.94**	**-0.64**	**-0.58**	**0.64**	**0.89**	0.02	0.24	0.01	**0.55**	**0.74**	0.15	-0.39	-0.36	-0.26	1.00	
MWD	0.13	**0.48**	0.47	-0.41	-0.31	0.38	0.45	0.17	-0.21	-0.24	0.45	0.23	0.33	-0.36	0.29	0.07	0.47	1.00
Midslope																		
BD	1.00																	
TC	0.09	1.00																
SCs	0.27	**0.98**	1.00															
Clay	-0.23	**-0.63**	**-0.67**	1.00														
Silt	0.16	-0.29	-0.23	0.38	1.00													
Sand	0.00	**0.51**	**0.49**	**-0.76**	**-0.89**	1.00												
P	-0.13	0.41	0.37	-0.43	-0.38	**0.48**	1.00											
K	-0.33	0.30	0.24	**-0.53**	**-0.65**	**0.71**	**0.60**	1.00										
Ca	0.18	-0.18	-0.16	0.14	0.08	-0.12	-0.34	-0.09	1.00									
Mg	0.07	-0.02	-0.02	0.19	0.26	-0.28	-0.12	-0.03	**0.81**	1.00								
Exch. Acidity	-0.28	0.26	0.20	-0.43	**-0.65**	**0.67**	**0.53**	**0.77**	0.06	0.06	1.00							
T cations	0.03	0.02	0.00	-0.11	-0.28	0.25	0.09	0.29	**0.81**	**0.71**	**0.56**	1.00						
Acid-sat	-0.35	0.23	0.17	-0.38	**-0.59**	**0.60**	0.45	**0.73**	-0.16	-0.14	**0.91**	0.28	1.00					
pH	0.33	-0.18	-0.11	0.30	**0.54**	**-0.53**	-0.30	**-0.65**	-0.19	-0.17	**-0.93**	**-0.61**	**-0.90**	1.00				
Zn	-0.10	0.28	0.23	-0.44	**-0.63**	**0.65**	**0.74**	**0.71**	0.11	0.07	**0.70**	**0.57**	0.46	**-0.55**	1.00			
Mn	-0.10	0.11	0.07	-0.23	-0.46	0.44	0.28	0.44	**0.53**	0.44	**0.77**	**0.91**	**0.50**	**-0.78**	**0.72**	1.00		
Cu	0.27	-0.25	-0.23	0.37	0.13	-0.27	-0.11	-0.21	**0.47**	**0.55**	-0.02	0.35	-0.10	-0.01	-0.07	0.11	1.00	
MWD	-0.14	0.38	0.34	**-0.66**	**-0.55**	**0.71**	**0.50**	**0.54**	-0.27	-0.40	0.29	-0.05	0.22	-0.09	**0.55**	0.10	-0.38	1.00
Downslope																		
BD	1.00																	
TC	-0.14	1.00																
SCs	0.05	**0.98**	1.00															
Clay	-0.10	-0.16	-0.18	1.00														
Silt	**-0.57**	0.04	-0.07	0.19	1.00													
Sand	0.42	0.09	0.16	**-0.80**	**-0.74**	1.00												
P	-0.01	0.25	0.27	0.03	-0.03	0.00	1.00											
K	0.04	**0.91**	**0.94**	-0.12	-0.02	0.10	0.31	1.00										
Ca	-0.05	-0.15	-0.17	0.15	0.08	-0.15	-0.32	-0.18	1.00									
Mg	-0.18	-0.43	**-0.50**	0.28	0.13	-0.27	-0.32	**-0.62**	**0.54**	1.00								
Exch. Acidity	-0.10	**0.66**	**0.65**	-0.27	-0.04	0.21	**0.51**	**0.66**	**-0.48**	**-0.63**	1.00							
T cations	-0.17	**0.69**	**0.67**	-0.21	0.01	0.14	0.46	**0.64**	-0.18	-0.39	**0.94**	1.00						
Acid-sat	0.00	**0.49**	**0.50**	-0.18	-0.08	0.17	**0.48**	**0.52**	**-0.67**	**-0.67**	**0.90**	**0.75**	1.00					
pH	0.07	**-0.57**	**-0.57**	0.17	0.06	-0.15	**-0.50**	**-0.55**	0.46	**0.50**	**-0.95**	**-0.91**	**-0.94**	1.00				
Zn	-0.17	**0.86**	**0.81**	-0.32	-0.04	0.25	0.01	**0.61**	-0.13	-0.22	**0.48**	**0.51**	0.35	-0.44	1.00			
Mn	-0.30	-0.33	-0.42	0.32	-0.02	-0.21	-0.11	**-0.57**	0.39	**0.83**	-0.34	-0.13	-0.31	0.15	-0.11	1.00		
Cu	-0.22	**0.89**	**0.86**	-0.06	0.11	-0.03	0.23	**0.77**	-0.02	-0.39	**0.74**	**0.81**	**0.57**	**-0.69**	**0.71**	-0.17	1.00	
MWD	0.12	0.01	0.02	-0.08	-0.29	0.23	-0.27	-0.16	-0.01	0.23	-0.34	-0.35	-0.37	0.41	0.26	0.15	-0.19	1.00

TC, total carbon; BD, soil bulk density; SCs, soil carbon stocks; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Exch. A, exchangeable acidity; T cations, total cations; Acid sat., acid saturation percentage; Zn, zinc; Mn, manganese; Cu, copper; MWD, mean weight diameter

Overall, soil C content in the subsoil (40-100cm) under tea plantation was 20–40% higher compared to undisturbed forest (Figure 5).

The correlation analysis indicate that in the upslope position, soil C content in the subsoil were positively correlated with copper (r = 0.92) phosphorus (r = 0.74), sand (r = 0.63), effective cation exchange capacity (r = 0.56), exchangeable acidity (r = 0.49), mean weight diameter (r = 0.48). Soil carbon stocks were positively correlated to copper (r = 0.94), phosphorus (r = 0.79), effective cation exchange capacity (r = 0.57) and exchangeable acidity (r = 0.48). Both soil carbon content and stocks were negatively correlated with silt and clay content (r = -0.60 and -0.61, respectively).

In the midslope position, soil C content and stocks were positively correlated sand content (r = 0.49-0.51) and negatively correlated to clay content (r = -0.63-0.67).

In the downslope position, soil carbon content was positively correlated with potassium (r = 0.91), copper (r = 0.89) zinc (r = 0.86), effective cation exchange capacity (r = 0.69), exchangeable acidity (r = 0.66), acid saturation (r = 0.49) and negatively correlated with pH (r = -0.57). Soil carbon stocks were positively correlated to potassium (r = 0.94), copper (r = 0.86), zinc (r = 0.81), effective cation exchange capacity (r = 0.67), exchangeable acidity (r = 0.65), acid saturation percentage (r = 0.50) and negatively correlated with magnesium (r = -0.50), and pH (r = -0.57).

3.4.4 Distribution of soil carbon content, soil bulk density and soil carbon stocks in the topsoil and subsoil

3.4.4.1 Distribution of soil carbon content in the topsoil and subsoil

In the topsoil of the upslope position, soil total carbon was lower in tea plantation (40.77 g C kg^{-1}) compared to undisturbed forest (53.08 g C kg^{-1}). High soil total carbon was observed tea plantation in both midslope (36.41 g C kg^{-1}) and downslope (44.68 g C kg^{-1}) position as compared to undisturbed forest. The highest soil total carbon throughout the topographic positions was observed in undisturbed forest in the upslope position.

In the subsoil of the upslope position, soil total carbon was higher in tea plantation (20.62 g C kg^{-1}) as compared to undisturbed forest (11.69 g C kg^{-1}). In the midslope, soil total carbon for both tea plantation and undisturbed forest was the same. In the downslope, soil total carbon followed a similar trend as in the upslope position where tea plantation (14.40 g C kg^{-1}) had a higher bulk density as compared to undisturbed forest (7.55 g C kg^{-1}). Tea plantation had an overall decline in soil bulk density throughout the topographic positions where the highest bulk density was observed in the upslope and the lowest in the midslope position.

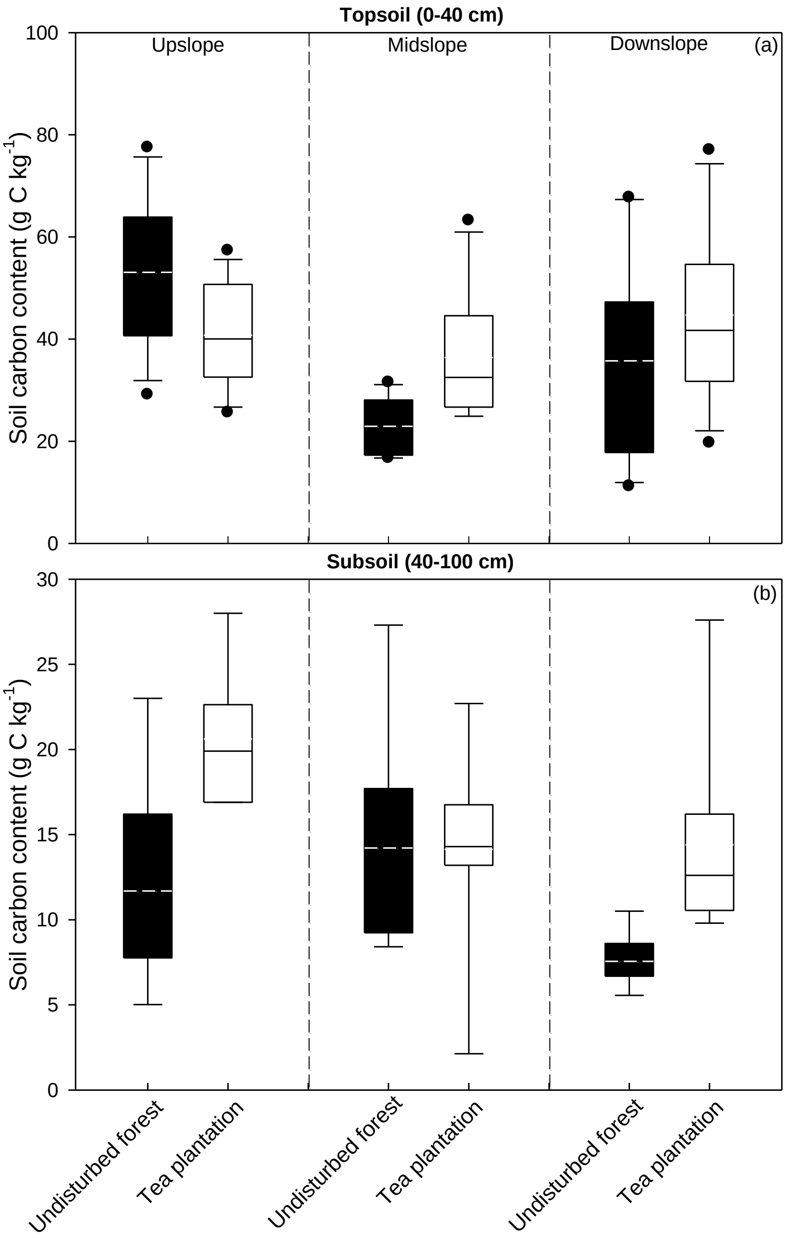

Figure 6: The mean and range of carbon content in the (a) topsoil and (b) subsoil of undisturbed forest (black) and tea plantation (white) land uses. The dashed line is the mean value, the solid line is the median, the box represents the upper and lower quartile, the whiskers are the 10th and 90th percentiles. The different lowercase letters indicate significant differences in SCC between the land uses, while the uppercase letters indicate significant differences among the topographic positions (Turkey's HSD test, $p \leq 0.05$)

3.4.4.2 Distribution of soil bulk density in the topsoil and subsoil

In the topsoil of the upslope position, soil bulk density in tea plantation was higher (0.96 g cm^{-3}) as compared to soil bulk density in the undisturbed forest (0.80 g cm^{-3}). In the midslope, soil bulk density was lower (0.89 g cm^{-3}) in tea plantation as compared to undisturbed forest (1.11 g cm^{-3}). In the downslope, soil bulk density followed a similar trend as in the upslope position where tea plantation had a higher bulk density (0.84 g cm^{-3}) as compared to undisturbed forest (0.82 g cm^{-3}). Tea plantation had an overall decline in soil bulk density with topographic position and the highest bulk density throughout the topographic positions was observed in the undisturbed forest of midslope position.

In the subsoil of the upslope position, soil bulk density was higher in tea plantation (1.03 g cm^{-3}) as compared to undisturbed forest (0.90 g cm^{-3}). In the midslope, soil bulk density was lower in tea plantation as compared to undisturbed forest. In the downslope, soil bulk density followed a similar trend as in the upslope position where tea plantation (0.97 g cm^{-3}) had a higher bulk density as compared to undisturbed forest (0.94 g cm^{-3}). Tea plantation had an overall decline in soil bulk density across the topographic positions where the highest bulk density was observed in the upslope and the lowest in the downslope position.

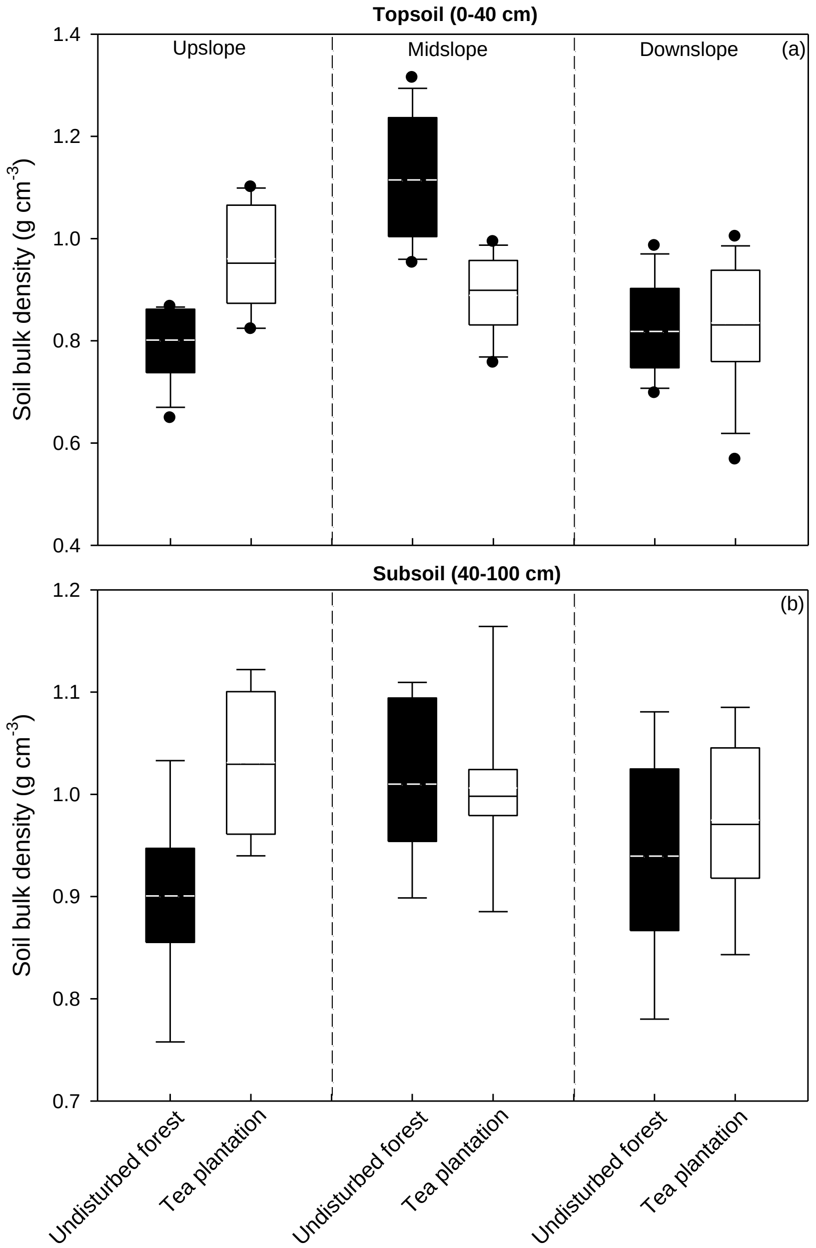

Figure 7: The mean and range of soil bulk density (BD) in the (a) topsoil and (b) subsoil of undisturbed forest (black) and tea plantation (white) land uses. The dashed line is the mean value, the solid line is the median, the box represents the upper and lower quartiles, the whiskers are the 10th and 90th percentiles. The different lowercase letters indicate significant differences in BD between the land uses, while uppercase letters indicate significant differences among the topographic positions (Tukey's HSD test, $p \leq 0.05$).

3.4.4.3 Distribution of soil carbon stocks in the topsoil and subsoil

In the topsoil of the upslope position, soil carbon stocks (SCs) were lower in tea plantation (3.54 kg C m^{-2}) compared to undisturbed forest (3.73 kg C m^{-2}). High SCs were observed tea plantation in both midslope (2.90 kg C m^{-2}) and downslope position (3.17 kg C m^{-2}) as compared to undisturbed forest. The highest SCs throughout the topographic positions were observed in undisturbed forest in the upslope position.

In the subsoil of the upslope position, SCs was higher in tea plantation (4.28 kg C m^{-2}) as compared to undisturbed forest (2.04 kg C m^{-2}). In the midslope, SCs for both tea plantation and undisturbed forest was the same. In the downslope, soil total carbon followed a similar trend as in the upslope position where tea plantation (2.76 kg C m^{-2}) had a higher bulk density as compared to undisturbed forest (1.39 kg C m^{-2}). Tea plantation had an overall decline in soil bulk density throughout the topographic positions where the highest bulk density was observed in the upslope and the lowest in the midslope position.

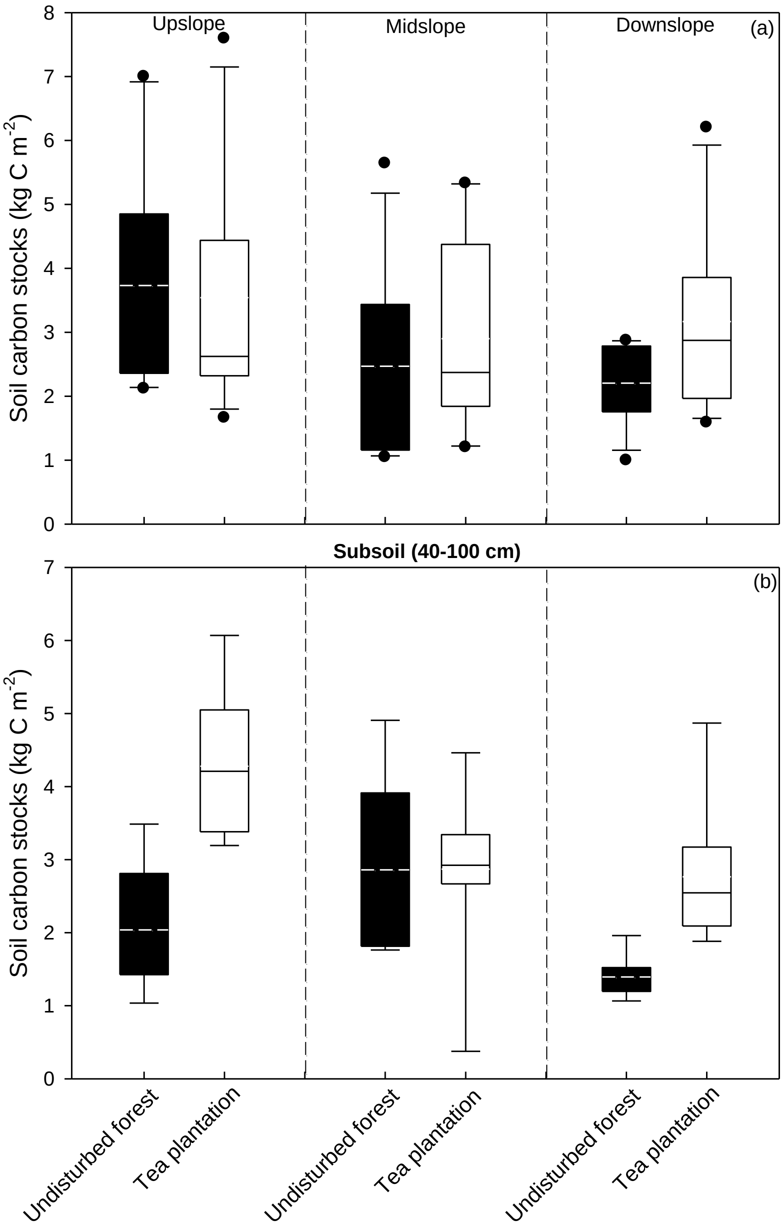

Figure 8: The mean and range of soil carbon stocks in the (a) topsoil and (b) subsoil of undisturbed forest (black) and tea plantation (white) land uses. The dashed line is the mean value, the solid line is the median, the box represents the upper and lower quartiles, the whiskers are the 10th and 90th percentiles. The different lowercase letters indicate significant differences in SCS between the land uses, while uppercase letters indicate significant differences among the topographic positions (Tukey's HSD test, $p \leq 0.05$).

3.5 Discussion

3.5.1 Effect of land use change from undisturbed forest to tea plantation on soil carbon content, stocks and bulk density

In many parts of the world, tea plantations have been established at the expense of native forests (Kamau *et al*., 2008). Several factors interact to determine soil organic matter following land use change (Scott *et al*., 1999). The current study found that soil C content was greater under tea plantation compared to undisturbed native forest, which were both sited on oxisols. The differences in soil C content observed between the two land uses can be attributed to the different land management practices that can either result in the accumulation or depletion of C in the soil. Further, several mechanisms, which differ between these ecosystems are involved in the distribution of soil C within soil profiles (Jobbágy and Jackson, 2000; Lorenz and Lal, 2005). The higher soil C content under tea plantation soils is caused by the periodical pruning and constant removal of the apical buds (Kamau *et al*., 2008), resulting in high aboveground plant residues. The conversion of natural ecosystems to agriculture entails a range of activities that affect rates of addition and decomposition of soil organic matter (Zinn *et al*., 2005). The tea plant residues left behind after pruning supply C into the soil when the organic material undergoes decomposition. The nutrients released from organic matter decomposition may result in long-term carbon gains under tea plantation. Conversely, total C inputs were lower in the adjacent undisturbed forest because most of the dry matter produced is held in the trees (Scott *et al*., 1999). Further, some studies have reported that a greater proportion of detrital C inputs in forests come from above-ground litterfall. These inputs, which are located on the soil surface may slowly decompose (Scott *et al*., 2006). The lower soil C content in the forest is also due to minimal soil disturbance, which results in low amount of litter fall and C inputs on the forest floor.

In both land uses, soil C content decreased gradually with depth. The low soil C below 30 cm reflects a lower composition of organic material with depth. This finding corroborates the study by Jobbágy and Jackson (2000) that found that the vertical distribution of soil carbon is strongly influenced by vegetation, as it changes the proportion of belowground inputs.

Carbon input into subsoils can also occur through transport of dissolved organic C (DOC) from the topsoil or through bioturbation of litter residues (Rumpel and Kögel-

Knabner 2011). This suggests that C inputs to the soil changed following land use change from undisturbed forest to tea plantation, and these changes influenced soil C storage. The accumulation of C in the soil is dependent on a balance between fresh C inputs and SOC respiration. With a land use change, SOC may increase when C inputs are greater than before but the concomitant increase in substrate for decomposition results in an equilibrium after some time (Davis *et al*., 2018).

Comparable studies by Li *et al*. (2011) found that tea plantations maintained a relatively higher C content in the topsoil layer (0-20 cm) than forests due to the decomposition of plant litter on the surface after harvesting. Zhou *et al*. (2000) reported greater total C storage in tea plantations (193.3 Mg C ha^{-1}) compared to forests (187 Mg C ha^{-1}) as result of higher biomass and plant litter.

Soils with high SOM content are more resilient to compaction when compared with those with low SOM content if all other factors remain the same (Yadav *et al*., 2019). Generally, increases in the SOM content increase structural stability, while a decline in SOM content increases soil compaction. The conversion of undisturbed forest to tea plantation was accompanied by changes in soil properties, specifically an increase in soil bulk density and these changes influence soil C storage. Our results are consistent with other studies elsewhere that reported higher bulk densities under tea plantations compared to undisturbed forests. Work by Islam and Weil (2000) found that conversion of forest to tea plantation increased soil bulk density in oxisols in Bangladesh. Illukpitiya *et al* (2004) reported that tea plantations in Sri Lanka had higher (47.3%) soil bulk density compared to adjacent undisturbed forest soils.

The greatest values of bulk density were observed under tea plantation due continuous trampling of the soil surface by workers during pruning, in the process destroying the soil structure. Soil compaction in tea plantation soils is a result of site preparation and manual harvesting (Hamza and Anderson, 2005). Soil bulk density is a surrogate that indicates pore space and soil compaction (Weil and Brady, 2017). The resulting compacted soil, created by trampling impairs the ability of soil to function. The higher bulk density and less stable aggregates may limit deeper root growth. Soil compaction in the subsoil layers may restrict deep root growth and adversely affect plant access to subsoil water (Chen and Weil, 2011).

The lower bulk density values under undisturbed forest can be attributed to the woody tree roots, which maintain soil porosity and structure, thereby avoiding compaction (Lia and Shao, 2006). In tea plantation the soil structure is exposed to deterioration by trampling during pruning. Compaction lowers soil C content due to a decline in root growth and plant development (Chen *et al*., 2017), and this results in decreased inputs of organic materials. Reichert *et al*. (2016) reported that compaction stunted plant growth and development due to poor root growth and reduced availability of water in compacted soil, resulting in low inputs of organic material to the soil surface, and thus decreasing soil carbon over time.

In some instances, the conversion of forest to croplands is not sustainable if conversion occurs on land that is not suitable for crop production (Joshi *et al*., 2019). Soil organic carbon stocks are controlled by the complex interplay of soil physical, chemical, and biological conditions (Li *et al*., 2020). Some studies have shown that land use conversion from forests to tea plantations severely affects the physical and chemical properties, nutrient cycling and overall soil fertility (Neil *et al*., 1997; Templer *et al*., 2005).

Carbon storage in soils is determined by the balance of bulk density and C content, with the trade-off between these factors resulting in increases or decreases in soil C stocks (Beesley *et al*., 2020). In this study, we found higher carbon stocks under tea plantation, which was also characterised by corresponding higher soil carbon content and bulk density.

In both land uses, soil carbon content and stock declined with depth in the Oxidic profiles, with the lowest values found deeper soil layers (80-100 cm). The lower soil carbon content and stock down the Oxidic profiles can be attributed to the low organic matter input down the profile (Conforti *et al*., 2016).

3.5.2 Factors controlling soil carbon content in the topsoil and subsoil

It is important not only to quantify the soil carbon content but also to identify the factors that control the content (Mayer *et al*., 2019). There is increasing evidence from literature that the factors controlling soil C may differ between topsoil and subsoil (Mayer *et al*., 2019). Our correlation analysis suggests two primary factors (physical and chemical stabilization) controlling soil carbon storage in the topsoil and subsoil of the Oxisol investigated in this study. In the topsoil, soil carbon content was correlated with mean weight diameter, a measure of soil aggregate stability and is sometimes used as a structural indicator (Zinn *et al*., 2007). Oxisols contain highly stable aggregates (Tisdall, 1996; Lima and Anderson, 1997), probably because of the cementing effect of Fe (Bigham *et al*., 2002) and Al (Huang *et al*., 2002) oxides in the clay fraction. However, annual cultivation of oxisols decreases aggregate stability. Soil aggregation has several benefits for agriculture and the environment as it enhances aeration, structure, water holding capacity and infiltration, which improves root establishment and plant growth.

The pruning of tea plants can also modify aggregate stability by introducing organic matter through litter fall (Kamau *et al*., 2008). Work by Zinn *et al* (2007) in the Brazilian Cerrado showed that SOC and MWD may not be strongly correlated in subsoil layers. The structural control on SOC retention, but also any potential aggregation effects of SOC, may be expressed only in the surface layer of those soils (Zinn *et al*., 2007).

SOC storage is strongly linked to plant inputs via the formation of soil organic matter, but soil geochemistry also plays a critical role (Sayer *et al*., 2019). In Oxidic soils with rapid SOC turnover, the association of organic matter with soil minerals is particularly important for stabilising SOC (Sayer *et al*., 2019). Indeed, previous studies have shown that that soil carbon can be directly related to the concentration and distribution of some heavy metals (Dlamini *et al*., 2019; Beesley *et al*., 2020).

The soil carbon content at our site was correlated with polyvalent cations and exchangeable bases. These polyvalent cations play an important role in chemical stabilization of soil carbon. They form complexes with organo-minerals in the soil (Dlamini *et al*., 2019). Chemical stabilization of soil carbon is also linked with the ability of exchangeable bases to bind organic matter with clay surfaces through electrostatic interactions (Dlamini *et al*., 2019; Tchienkoua and Zech, 2004). Microorganisms found in oxisols are unable to breakdown the chemically stabilized soil carbon or decompose the organic matter thus promoting the accumulation and availability of soil carbon (Rowley *et al*., 2018).

Furthermore, SC in our study was negatively correlated to pH and positively correlated with heavy metals; zinc, copper and manganese. Following land use conversion from undisturbed forest to tea plantation, the soil becomes strongly acidic as shown in our study where soil pH decreased from 4.19 (undisturbed forest) to 4.04 (tea plantation).

The strong correlation of soil carbon content and stock in the topsoil can be linked to the acidic soil pH, which generally increases the availability of metal ions (Han *et al*., 2013). Soil pH has a considerable effect on the availability of heavy metals. In acidic conditions metals exist as free ionic cations. Soil pH generally increases the availability of metal ions and is well known for mobilising metals. In this study, topsoil had the highest soil acidity across all the topographic positions and decreased with depth. Heavy metals provide chemical protection of SC by binding or forming bridges with soil organic matter in the soil. The complexation with the soil organic matter also leads to the availability these micronutrients or heavy metals to the plants (Sparks, 2003).

The stability of SC varies among horizons of a soil type due to differences in chemical and physical properties (Parras-Alcántara *et al*., 2015). Other studies indicate that the chemical composition of SOC in the subsoil is affected by pedological processes and is therefore soil type specific (Rumpel *et al*., 2002; Eusterhues *et al*., 2005). In both land uses, the topsoil (0–40 cm) had significantly greater SC and SCs than the subsoil (40-100 cm) in all the topographic positions. In our study, the primary controlling factor of soil carbon content and stocks in the subsoil was chemical stabilization. Soil carbon and stocks were strongly positively correlated with polyvalent cations, exchangeable bases and heavy metals. The correlation values were higher than those in the topsoil, therefore the chemical stabilization of soil carbon and stocks is much more stronger in the subsoil than in the topsoil.

3.5.3 Topographic effect on soil carbon content and stocks

Topography affects soil C through erosion and redistribution of fine soil particles and organic matter across landscape (Senthilkumar *et al*., 2009). Topographic position also accounted for considerable variation in soil carbon content and stocks, with downslope positions exhibiting greater carbon levels. Our findings support previous studies that have found a link between soil carbon and topography (Berhe *et al*., 2008). Notably, greater soil carbon content and stocks were found in the lower lying slope position (downslope).

The higher soil carbon in the downslope position is possibly due to surface erosion and deposition of soil carbon from upslope to lower lying slope positions of the hill slope. SC and SCs are also protected in the downslope from further decomposition due to burial from the soil and sediments deposited from upslope (Smith *et al*., 2001).

Soil carbon content and stocks were found to be lower at higher elevations (upslope) possibly due to the downward transport of nutrient-rich sediments and leaching of basic cations from upper hill slope sections (Berhe *et al*., 2008).

3.6 Conclusion

This study assessed the vertical distribution of soil carbon content and stocks under tea plantation compared to an adjacent undisturbed forest, and (2) determined the controlling edaphic factors. The results showed that carbon content and stocks were greater under tea plantation than in the undisturbed forest. Correlation analysis revealed that carbon content in the topsoil was positively correlated with heavy metals, effective cation exchange capacity and soil aggregate stability, while in the subsoil, carbon content was negatively correlated with clay content and pH. This finding suggests that soil carbon content and stocks are chemically stabilised by polyvalent cations and physically retained by aggregates in the topsoil. Furthermore, carbon stocks in the topsoil were positively correlated with acid saturation and negatively correlated with effective cation exchange capacity, manganese and exchangeable cations (calcium, magnesium and potassium). In the subsoil, the carbon stocks were negatively correlated with clay content and pH. Future work will investigate the distribution of C within soil micro-and macro-aggregates of tea plantation oxisols and investigate the role of iron and aluminium oxides in stabilizing the C.

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CHAPTER 4

SUMMARY AND CONCLUSION

The overall aim of this dissertation was to investigate the long-term effect of tea plantation compared to undisturbed forest reference site on the carbon content and stocks of oxisols. In chapter 3, a study was conducted to quantify and compare soil carbon and stocks under tea plantation and undisturbed forest, and evaluate the edaphic factors influencing the vertical distribution of soil carbon and stocks under both land uses. Long term changes were determined by comparing soil carbon and stocks content in the reference site (undisturbed forest) and tea plantation. Spatial variability was evaluated by comparing soil carbon and stocks across varying topographic positions, the results revealed that there was no spatial variability since soil carbon and stocks in varying topographic positions was controlled by the same soil physical and chemical properties.

It was shown in the results that tea plantation led to an increase of soil nutrients which then decreased with depth across the topographic positions. In order to maintain high yielding and high quality tea plantations, organic manure should be used instead of inorganic fertilizers, this will improve carbon storage in tea plantation soils. Application of soil amendments such as dolomite is important in maintaining the soil acidity in tea plantations at a satisfactory level. Terraces and mulch can be used in the upslope to avoid soil erosion.

The study also uncovered some areas of research that could be addressed in the future. There is a need to further investigate the iron and aluminium oxides in this soil in order to get a better understanding of their interactions with soil carbon storage as there is no clear consensus as to how they stabilize soil carbon and if they are the primary soil carbon stabilizers in oxisols. Future work will also look at soil carbon distribution within micro and macro aggregates to determine whether soil texture play a role in the stabilization of soil carbon and how it relates to topographic effects. This will provide information of where most of the soil carbon is located within the aggregates and whether it is stored long term or short term.

APPENDICES

Appendix 1: Pedological characteristics of profile 1 under tea plantation land use

Location: Tshivase tea estate pit 1

Classification: oxidic soils (hutton)

Sampling date: 27 March 2018

Longitude: 030, 32794°

Latitude: 22, 95606°

Elevation: 935 m.a.s.l.

Topographic position: mid slope

Pit height: 1 m

Drainage: well drained

Parent material: dolorite

Vegetation: tea

Faunal activity: high activity of earth worms

Land use: tea plantation

Top soil: Orthic A 0-40 cm, reddish brown (2.5YR4/4), sandy clay loam, slightly moist, weak structure, many fine roots, gradual smooth boundary

Subsoil: Red apedal B 40-100 cm, red (2.5YR 4/8) clay loam, slightly moist, weak structure, many fine roots

Appendix 2: Pedological characteristics of profile 2 under tea plantation land use

Location: Tshivase tea estate pit 2

Classification: oxidic soils (hutton)

Sampling date: 27 March 2018

Longitude: 030, 32778°
Latitude: 22, 95641°
Elevation: 930 m.a.s.l.

Topographic position: upslope

Pit height: 1 m

Drainage: well drained

Parent material: dolorite

Vegetation: tea

Faunal activity: high activity of earth worms

Land use: tea plantation

Top soil: Orthic A 0-40 cm, reddish brown (2.5YR4/4), sandy clay loam, slightly moist, weak structure, many fine roots, clear smooth boundary

Subsoil: Red apedal B 40-100 cm, red (2.5YR 4/8) clay loam, slightly moist, weak structure, many fine roots

Appendix 3: Pedological characteristics of profile 3 under tea plantation land use

Location: Tshivase tea estate pit 3

Classification: oxidic soils (hutton)

Sampling date: 28 March 2018

Latitude: 22, 95518°

Longitude: 030, 32799°

Elevation: 915 m.a.s.l.

Topographic position: downslope

Pit height: 1 m

Drainage: well drained

Parent material: dolorite

Vegetation: tea

Faunal activity: high activity of earth worms

Land use: tea plantation

Top soil: Orthic A 0-40 cm, reddish brown (2.5YR4/4), sandy clay loam, slightly moist, weak structure, many fine roots, gradual smooth boundary

Subsoil: Red apedal B 40-100 cm, red (2.5YR 4/8) clay loam, slightly moist, weak structure, coarse roots

Appendix 4: Pedological characteristics of profile 4 under undisturbed forest land use

Location: Tshivase tea estate pit 4

Classification: oxidic soils (hutton)

Sampling date: 28 March 2018

Latitude: 22, 95496°

Longitude: 030, 32849°

Elevation: 883 m.a.s.l.

Topographic position: upslope

Pit height: 1 m

Drainage: well drained

Parent material: dolorite

Vegetation: trees and grasses

Faunal activity: earth worms

Land use: undisturbed forest

Top soil: Orthic A 0-40 cm, reddish brown (2.5YR4/4), sandy clay loam, slightly moist, weak structure, coarse roots, clear smooth boundary

Subsoil: Red apedal B 40-100 cm, red (2.5YR 4/8) clay loam, slightly moist, weak structure, coarse roots

Appendix 5: Pedological characteristics of profile 5 under undisturbed forest land use

Location: Tshivase tea estate pit 5

Classification: oxidic soils (hutton)

Sampling date: 27 March 2018

Latitude: 22, 95598°

Longitude: 030, 32532°

Elevation: 947 m.a.s.l.

Topographic position: midslope

Pit height: 1 m

Drainage: well drained

Parent material: dolorite

Vegetation: grass and trees

Faunal activity: none observed

Land use: undisturbed forest

Top soil: Orthic A 0-40 cm, reddish brown (2.5YR4/4), sandy clay loam, slightly moist, weak structure, many coarse roots, gradual smooth boundary

Subsoil: Red apedal B 40-100 cm, red (2.5YR 4/8) clay loam, slightly moist, weak structure, many coarse roots

Appendix 6: Pedological characteristics of profile 6 under undisturbed forest land use

Location: Tshivase tea estate pit 6

Classification: oxidic soils (hutton)

Sampling date: 28 March 2018

Latitude: 22, 95529°

Longitude: 030, 32600°

Elevation: 925 m.a.s.l.

Topographic position: downslope

Pit height: 1 m

Drainage: well drained

Parent material: dolorite

Vegetation: grass and trees

Faunal activity: none observed

Land use: undisturbed forest

Top soil: Orthic A 0-40 cm, reddish brown (2.5YR4/4), sandy clay loam, slightly moist, weak structure, many coarse roots, gradual smooth boundary

Subsoil: Red apedal B 40-100 cm, reddish brown (2.5YR 4/4) clay loam, slightly moist, weak structure, many coarse roots