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What Drives Decline Productivity in Ageing Tea Plantation- Soil Physical Properties or Soil Nutrient Status?

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Abstract

Over the years, the tea plantations in the Ribeira Valley, Brazil had been recording declining productivity and reduced tea quality. This had been associated with several factors including the age of the plantation, decling fertility, soil degradation among others factor. In this study, our objective was to identify the main driver of declining productivity in tea yield in the Ribeira Valley tea plantation in Brazil and to evaluate the effects of long-term tea cultivation on the physico-chemical changes and nutrient dynamics in the soil at 2 profile depths. Therefore, we evaluated the effects of long-term cultivation on changes in the physical and chemical properties of Acrisol Haplic planted to Tea in the Ribeira Valley region, Brazil. The soil samples were collected at two depths 0-10 cm and 10-20 cm in two representative plantations and analyzed for chemical, physical and mechanical soil properties. The selected sites; Thea Hills – TH_{1987} and Braço Preto – BP_{1972} presents different plantation ages on a similar cultivation practices. The harvested quantities of tea from the sites were monitored and their quality classified following international standards. We observed declining productivity in terms of harvested tea from both sites and the quality of harvested tea were better in TH_{1987} than BP_{1972}. The soil nutrient study indicated an improvement in fertility parameters in the older plantation (BP_{1972}). We observed degradation in the soil physical quality parament and all possible factors indicated that degradation of the soil structure through compaction was the main factor resulting in the observed declined productivity (quantitatively and qualitatively). Soil structure degradation adversely affects the soil functions including aeration, crop water use efficiency and soil nutrient conversion. We recommend appropriate soil tillage management in tea plantations too improve the productive cycle and capacities.

Keywords: soil compaction, degradation of soil structure, soil fertility, soil penetration resistance.

1. Introduction

Tea, *Camellia sinensis* (L.) is widely cultivated around the world with about 2.72 million ha of land under tea cultivation globally (International Tea Committee, 2004). The variety *sinensis,* also called "China tea" grows suitably well in marginal areas of the subtropics and it is noted for drought-tolerance and can survive short frost periods (Kamau, 2008; Wang, Xu, Wang, & Li, 2010). In Brazil, Tea productction is mainly from the Ribeira Valley region (São Paulo State) with about 5000 ha land area cultivated. The tea culture has significant effect on the region's economy, both in terms of the labor absorbed by its exploration and industrialization, as well as the generation of foreign exchange (Sakai, 1997).

Inspite of increased overall productivity of the tea plantations worldwide, there are concerns on the stagnation and/or declining yields in the last two decades in the older tea plantations (40 years old and above). These plantatition although established with sufficient gaps (more than 25%) no longer respond positively to known agronomic practices (Kamau, 2008; Dutta, Stein, Smaling, Bhagat, & Hazarika, 2010). This had been similarly noted in Tea production from the RibeiraValley of Brazil, with consequent declining quantitative and qualitative productivity. According to Perez and Freitas (2003), between 1983 and 1994, the area under tea cultivation was 5,376 ha produceing 46,694 tons, which corresponded to an average yield of 8.69 t ha^{-1}. However, between 1995 and 2002, the harvestable area fell to 3,701 ha (31% reduction) producing 32,014 tons (32% reduction); an average of 8.65 t ha^{-1}. According to Instituto Brasileiro de Geografia e Estatística [IBGE] (2003), in 2003, the harvestable area reduced to 2,620 ha (51% reduction compared to 83/94) and produced only 21,020 tons (55% reduction over the same period), with quantitative productivity declining to 8.02 t ha^{-1}. In 2006 the harvested area was 2,505 ha (53% reduction compared to 83/94) and produced only 17,430 tons (63% reduction compared to 83/94), reaching a yield of 6.96 t ha^{-1}. The implication of the presented data is that the overall productivity in tea plantation Ribeira Valley region within the period analyzed fell by 20%.

According to Kamau (2008), peak yields (quantitative and qualitative) in tea plantation are obtained between 20-40 years after planting, followed by a decline to a level where the plantations may become degraded and uneconomical. Several hypotheses have been postulated on the driver of this decline productivity. However, several questions remained unanswered are unclear. Thus the the question remains: is it the tea bush that degrades, or the tea plantation soil or both? And, what is the right age to uproot the tea plantation and replant?

Jayasuriya (2003) had shown that the long-term exploitation of soils in tea gardens can lead to soil degradation. Similarly Wang *et al.* (2010) related changes in certain soils properties with years of tea cultivation. These authors observed that the cultivation of tea plants caused soil acidification. Soil acidity was observed to increase with the age of the tea plantation as the amount of soil exchangeable base cations decreased. Beyond soil chemical changes, various years of tea cultivation can alter soil structure too. Soil structure is one of the most important factors that moderate the availability of air and water to plant roots, nutrient supply, mechanical resistance to penetration and root development (Iori, Dias Junior, & Silva, 2012). Therefore, maintaining a physically good and stable soil structure is an essential condition to ensure high agricultural productivity (Corrêa, 2002). Dey (1969) regards a deep and well drained soil, with a minimum depth of two metres and an aggregated or crumb soil structure of about 50% pore spaces as the most important soil physical requirement for tea plant production.

The aim of this study is therefore to identify the main driver of declining productivity in tea yield in the Ribeira Valley tea plantation in Brazil. Therefore, the specific objective of the study was to evaluate the effects of long-term tea cultivation on the physico-chemical changes and nutrient dynamics in the soil at 2 profile depths.

2. Material and Methods

2.1 Study Area

This study was conducted in tea plantations located in the Pariquera-Açu municipality, São Paulo State, Brazil (24°37' S; 47°50' W). The climate according to Koppen is CFA; subtropical humid (Silva, Iori, & Silva, 2009), with an average annual temperature of about 21°C. The average annual rainfall is 1761 mm with the highest concentration in the months from November to March (Silva, Iori, Armesto, & Bendini, 2010). The soil of the study area was classified as an Acrisol Haplic (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2006) with 230 g kg^{-1} of clay, 367 g kg^{-1} of sand, 403 g kg^{-1} of silt (Loam soil texture according to USDA system) and particle density of 2.54 g cm^{-3}.

2.2 Study Factors

Two plantation ages were chosen: The Thea Hills - TH_{1987}, planted in 1987 (22 years) and Braço Preto - BP_{1972} planted in 1972 (37 years). Mechanical impact on soil structure in both planations is due only to the entry of small harvesting machines, developed by the farm owner for the local topography. However, despite the low weight of the harvester (5884 N when empty) or (6619.5 N) when loaded with tea leaves or the shoot , its average tires contact pressure reaches values of order 46.35 kPa due to the contact area (0.0357 cm^2).

2.3 Soil Analysis

Two sets of undisturbed soil cores were collected in the topsoil (0-10 cm) and the subsurface layer (10-20 cm) in 30 replicates. Texture and water dispersible clay (WDC) was determined by pipette method (Page, Miller, & Keeney, 1982), and the flocculation index (FI) was derived from the expression:

$$FI= [(C - WDC)\ C^{-1}]\ 100 \quad (1)$$

where, *FI* is the flocculation index in percentage; *C* is the total clay content (g kg^{-1}) and *WDC* is the water dispersible clay (g kg^{-1}). The paraffin clod method was used to measure the soil bulk density (Blake & Hartge, 1986) and total porosity (TP) was calculated using the expression:

$$TP\ (\%) = [1 - (BD - PD^{-1})]\ 100 \quad (2)$$

where, *TP* (%) is the total porosity (%), *PD* is the particle density (g cm^{-3}) and *BD* is the soil bulk density (g cm^{-3}). The particle density (*PD*) was determined by the volumetric flask method according to EMBRAPA (1997), based on the expression:

$$PD = a\ (50 - b)^{-1} \quad (3)$$

where, *PD* is the particle density (g cm^{-3}); *a* is the weight of sample dried at 105 ° C and *b* is the volume of alcohol spent. Organic Matter (*OM*) was determined using the wet combustion method (Liu, Jiang, & Zhang, 1996). The stability index (*SI*), which indicates the level of organic matter required to maintain the structure, was obtained based on the expression of Pieri (1992):

$$SI = [OM\ (C + S)^{-1}]\ 100 \quad (4)$$

where, *SI* is the Stability Index (%); C is the clay content (%); S is the silt content (%) and OM organic Matter content (%). Penetration Resistance was measured with the FALKER model PLG1020 digital penetrometer. The cone shape (2 x 12.83 mm) penetrometer is driven up to 50 cm into the soil with resistance measurement taken every 1cm and electronically stored. The volumetric water contents (θ) were adjusted according to the matric potential Ψm, to obtain the SWRC (Soil Water Retention Curves) following the model proposed by Van Genuchten (1980) by the following equation:

$$\theta = \theta_r + (\theta_s - \theta_r)/[(1+ (\alpha \quad \square_m)^n]^m \tag{5}$$

where, *θ* is volumetric water content; *θs* and *θr* are the saturation and residual water contents respectively; ψ_m is the tension in kPa; α, m and n represent the empirical parameters for the fitted model. The available water capacity (*AWC*) was determined as the difference in water content related to the matric potential at field capacity (*FC*) through the point of inflection of the curve and permanent wilting point *PWP* was 1500 kPa).

Soil *pH* was determined from the solution obtained after dissolving 10 $cm^3$of soil in 25 mL of H_2O. The sample chemical properties (P – phosphorus, K – potassium, Ca – calcium, Mg – magnesium, V – base saturation, SB – sum of bases, t – cation exchange capacity in natural pH, T – cation exchange capacity at pH 7.0, Al – aluminum, H+Al – hydrogen + alumínio e m – aluminum saturation.) were analyzed following the Brazilian standard procedures describe in EMBRAPA (1997).

2.4 Plantation Analysis

Quantitative yield data for the plantation were monitored from a reperestative10 m^2 grid and obtained data were extrapolated over the respective coffee plantation. The quality of the tea was also concurremtly evaluated from the tea harvested from the 10 m^2 grid by classifiying into internatianaly accepted categories: A, A1, B, B1 and C. The qualitative categorisattion is dependent on the degree of maturaty, levels of impurities and development of the bud. With this, the outputs were more easily related to the observed soil attributes.

2.5 Statical Analysis

Significant differences in soil attributes were identified using ANOVA *F*-test and Tukey test at 5% level. When graphically presenting the results, we decided on Error bars that represent the 95% confidence interval, which according to Paes (2008) may be more appropriate when it comes to making inferences about the means. The construction of graphs and charts was performed using the demo version of the application Sigma Plot 10.0 (Systat Software Inc).

3. Results

3.1 Productivity and Quality of Tea

Productivity (qualitative and quantitative) for the 2 plantations is preseted Figure 1. The result showed that average productivity from the plantations were significantly different; with the the younger TH_{1987} plot being more productive than the older BP_{1972} plot. Similarly, the quality parameters also indicated differences between the plots. While the younger plot produced 29% and 71% of tea type B and B1 respectively, the older plantion had 5% B, 90% B1 and 15% type C (Figure 1).

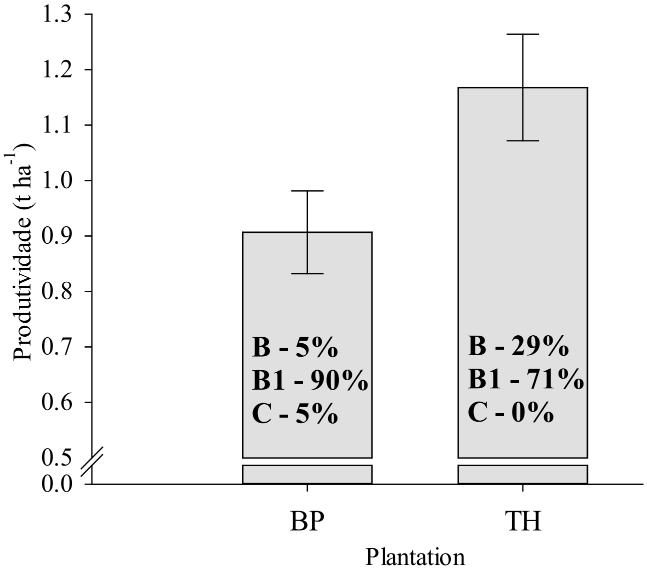


Figure 1. Yield and quality parameters of the tea from the studied plantations (TH – Thea Hills and BP – Braço Preto). The letters B, B1 and C represent classification for the quality of tea harvested.

3.2 Soil Chemical Attributes

Table 1 presents the chemical properties of the soil colleceted from the 2 plots at both surface and subsurface layers.

Table 1. Chemical charcateristics of the Thea Hills Farm and BraçoPreto Farm at the topsoil layers (0.0-0.1 m) and sub-surface (0.1-0.2 m)

Chemical attribute*	Thea Hills (1987)		Braço Preto (1972)	
	Topsoil (0..0-0.1 m)	Sub-surface (0.1-0.2 m)	Topsoil (0.0-0.1 m)	Sub-surface (0.1-0.2 m)
P (mg dm^{-3})	7.83 Ba	3.17 Ba	48.48 Aa	20.47 Ab
K (mg dm^{-3})	87.63 Ba	71.5 Ba	168.17 Aa	176.7 Aa
Ca (cmol$_c$ dm^{-3})	1.3 Ba	1.17 Ba	2.02 Aa	2.13 Aa
Mg (cmol$_c$ dm^{-3})	0.52 Ba	0.43 Ba	0.69 Aa	0.71 Aa
V (%)	17.25 Aa	15.48 Aa	16.79 Aa	18.5 Aa
SB (cmol$_c$ dm^{-3})	2.05 Ba	1.77 Ba	3.14 Aa	3.29 Aa
t (cmol$_c$ dm^{-3})	4.69 Ba	4.48 Ba	7.36 Aa	7.24 Aa
T (cmol$_c$ dm^{-3})	12.63 Ba	12.46 Ba	20.18 Aa	19.64 Aa
pH water	4.39 Aa	4.37 Aa	4.33 Aa	4.39 Aa
Al (cmol$_c$ dm^{-3})	2.65 Ba	2.69 Ba	4.22 Aa	3.94 Aa
H+Al (cmol$_c$ dm^{-3})	10.58 Ba	11.67 Ba	17.04 Aa	16.35 Aa
m (%)	56.00 Aa	60.77 Aa	57.57 Aa	54.13 Aa

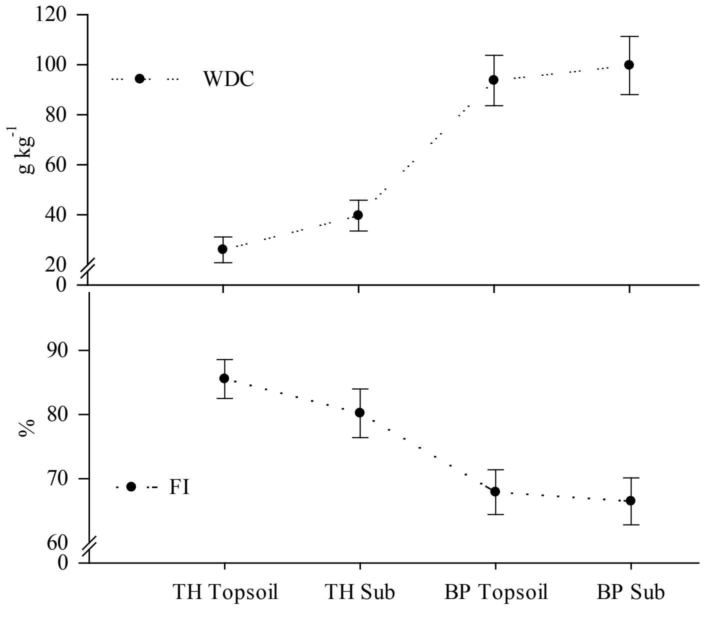
* P – phosphorus, K – potassium, Ca – calcium, Mg – magnesium, V – base saturation, SB – sum of bases, t – cation exchange capacity in natural pH, T – cation exchange capacity at pH 7.0, Al – aluminum, H+Al – hydrogen + alumínio e m – aluminum saturation. Capital letter (A and B) compares farms (TH and BP) in the same soil layer, at a significance level of 5% by Tukey test. Small letter (a and b) compares soil layers (surface and sub-surface) on the same farm at the significance level of 5% by Tukey test.

The range of values for most of the elements *K, Ca, Mg, SB, t, T, H + Al* and *Al* (Table 1) were similar in both tea planatiations and at both studied layers. However, higher values of were found in BP$_{1972}$ whe compared with TH$_{1987}$ for the two studied layers. For these elements, the values at the surface and sub-surface layers showed no significant differences ($P < 0.05$) among themselves. For Phosphorous, the behavior was different at the 2 plantations with the highest values observed at BP$_{1972}$ independent of the studied layer. In TH$_{1987}$, the values of P at both layers were statistically similar ($P < 0.05$). However, at BP$_{1972}$, we observed significant difference ($P < 0.05$) between the layers, with higher P contents in the topsoil layer. For V, pH and m (Table 1), the behavior of older tea plantation (TH$_{1987}$) was similar to the younger tea plantation (BP$_{1972}$) in both layers.

3.3 Soil Physical Attributes

For both studied soil depths in the two planatation we present the water-dispersible clay (WDC), flocculation index (FI), bulk density (BD) and total porosity (TP) in Figure 2. The TH$_{1987}$ plot had the lower and higher values of water and dispersed clay flocculation index respectively.

The BD and TP had similar behavior (Figure 2), which shows that there were significant differences between the plots for the two layers studied. However, the two layers of soil behaved similarly within each plot, both for BD and TP. Penetration resistances (PR) in the 0.5 m depth were higher in the BP$_{1972}$ when compared to the TH$_{1987}$ (Figure 3). The highest values of PR values were found in the soil layer between 0.08 m and 0.28 m at both sites, although the values in TH$_{1987}$ plantation were consistently higher.



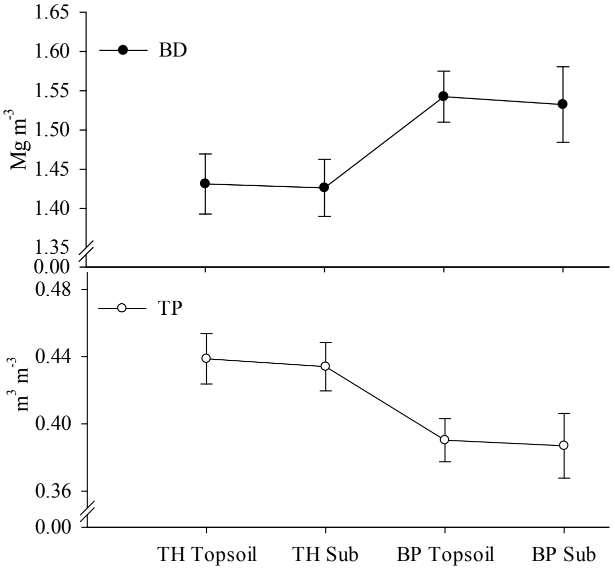


Figure 2. Water-dispersible clay (WDC), flocculation index (FI), bulk density (BD) and total porosity (TP) of soil for each plot studied (TH – Thea Hills and BP – Braço Preto) at two depths (Topsoil - 0 to 10 cm and Sub-surface - 10 to 20 cm)

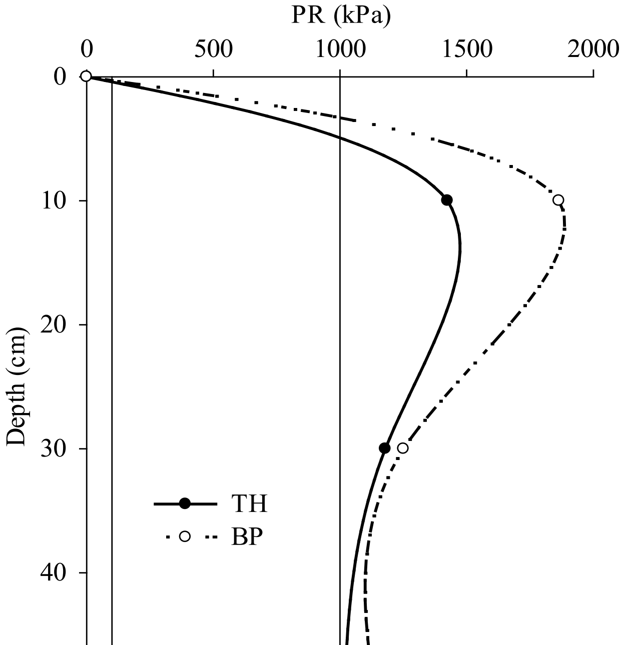


Figure 3. Soil resistance to penetration (PR) for depth from 0 to 50 cm in the soil for each plot studied (TH – Thea Hills and BP – Braço Preto) for depth from 0 to 20 cm

The major differences in water retention were mainly obtained at high tensions. At a tension of 2 kPa, the TH_{1987} plot soils had higher moisture retention, while at other points along the curve the BP_{1972} plot soils retained more water. However, the largest differences were only observed at tensions above 10 kPa. The observed difference in water retention (Figure 4) was due to the increase of textural pores, which are related to this particle size fraction between BP_{1972} and TH_{1987}. Thus, as the organic matter content was similar among the plots, the retention at low suctions did not show great variation between them either. Using the point of inflexion on the curve as an index of field capacity (8.02 for TH_{1987} and 10.45 kPa for BP_{1972}) and 1500 kPa as the permanent wilting point, the AWC was 23.4% for the TH_{1987} plot and 19.0% for the BP_{1972} plot.

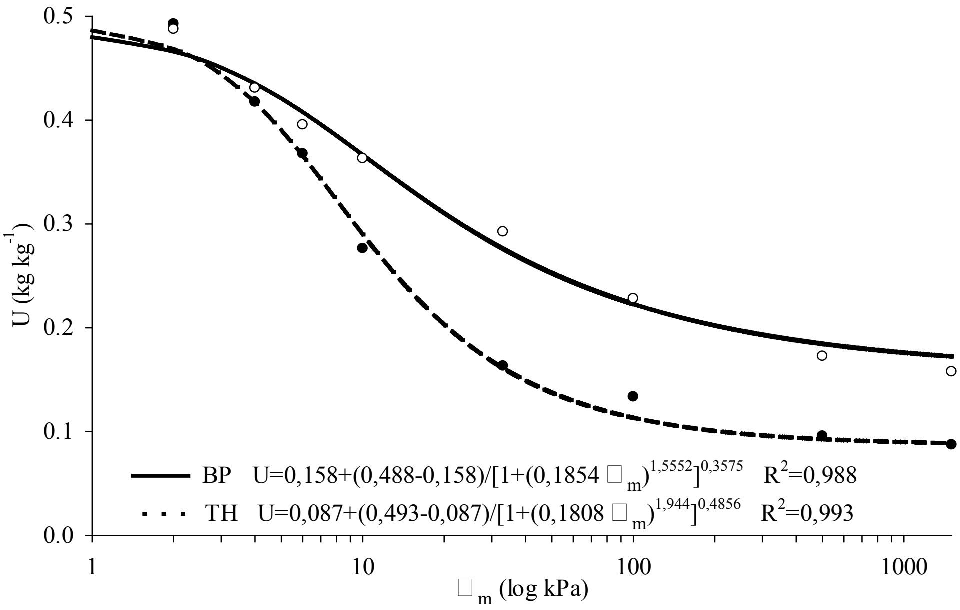


Figure 4. Curve of water retention in the soil for each plot studied (TH – Thea Hills and BP – Braço Preto) for depth from 0 to 20 cm

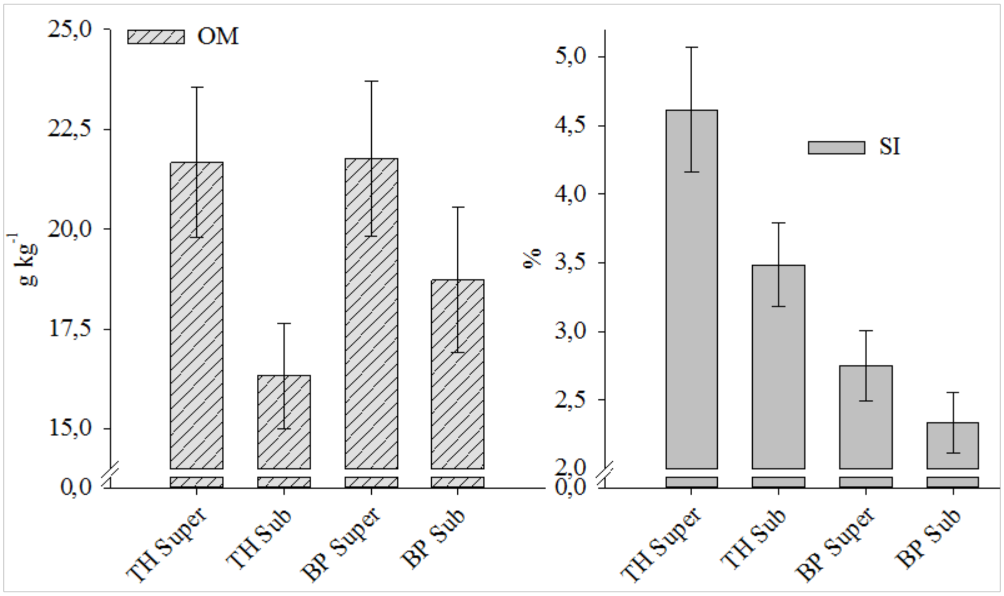


Figure 5. Levels of soil organic matter (OM) and stability index (SI) for each plot (TH –Thea Hills and BP – Braço Preto) at two depths (Topsoil - 0 to 10 cm and Sub-surface - 10 to 20 cm)

Unlike the other elements discussed above, the OM content showed no significant differences between the two tea plantations while the differences in layers within the same site were significant. Expectedly, the topsoil layer had higher values than the sub-surface layers. The soil structure stability index values were higher in TH_{1987} and than BP_{1972} at both layers (Figure 5).

4. Discussion

Worldwide, Tea quality is classified into A, A_1, B, B_1 and C with A being the premium grade while C is considered market worthy but generally with lowest market value. Brazil does not produce the premium grade Tea A and A_1, thus the best tea quality from Brazil peaks at Class B. The younger plot in this study TH_{1987} presented the best tea category and had no low end type C grade. This indicates that the best quality (relatively) of Tea were produced on the younger plantation. It should be noted that the prices of tea, like most agricultural products, vary according to quality, so the presence of type C reduces the price of the product in the international market. Similar to our observation in this study, younger tea bushes have been associated with high productivity in most tea-growing areas, and conversely, old tea bushes with declining productivity (Illukpitiya, Shanmugaratnam, & Kjosavik, 2004). Since the early 1980s, some of the older tea plantations in Kenya were observed to stagnate and/or decline in yields and did not respond to known agronomic practices (Mwakha, 1983; Mwakha, 1989). Dutta *et al.* (2010) in his work, suggest a parabolic relationship between tea yield and age, with production peaks generally falling between the ages 20 and 40 years and decline afterward. Kamau (2008) found significant differences in mean yield between the two tea sectors in Kenya, which are mainly related to age of tea plantations, there, differences in management practices and the use of tea genotypes.

Long-term tea (mono) cropping has also been implicated for "soil sickness" caused by a combination of soil pathogens, mineral depletion, change in soil structure and accumulation of toxic substances, amongst others (Owuor, 1996). This may lead to physical, chemical and biological soil degradation and ultimately to a decline in yield of the older tea plantations (Kamau, 2007). For soils of the tropics regions, the OM may constitute an important source of potential acidity in the soil. However, in this study, the results for potential soil acidity (H + Al) for both sites (TH_{1987} and BP_{1972}) were not different and followed the pattern of the OM. In the the managemnt practices adopted in Ribeira Valley Tea plantations, OM plays an important role in nutrient recycling.It has been recognized that intensive soil management practices could lead to large-scale depletion of OM and consequent degradation of soil quality (Yang, 2006; Wang, Cai, Hoogmoed, Oenema, & Perdok, 2007).

Since the human action or inadequate management of the soil can changes the its attribute, or even promote the degradation of its quality with consequences on production and sustainability of cultivation.

Soil acidity at the two studied sites was high confirming Wang *et al.* (2010) conclusions that the cultivation of tea plants accelerates soil acidification. These authors indicated soil acidity increased with increasing age of tea plantation. The elevated aciditywas observed at the two studied layers. The main sources of acids in the agricultural ecosystems are considered to be the soil and plant processes associated with the C and N cycle. For this study, the difference of 15 years between the two farms was not sufficient to cause differences in pH values. This was different from the observation of Wang *et al.* (2010) that acaidity level increases with age of tea plantation. Yang (2005) suggested that the excretion of organic acids, such as oxalic acid, citric acid and malic acid, as the main interior proton source for soil acidification in the tea plant-soil systems. Similarly, Cregan and Scott (1998) observed that application of large amounts of ammoniacal nitrogen fertilizer perhaps explaine the source of acidification of agricultural soil systems and specifically in tea gardens.

Acidity level was not sufficient to explain the notable difference in tea production and quality in the studied sites as there were no statistical differences between the 2 tea plantations ages studied. Tea plant is noted to grow best at (pH) ranging from 4.0 and 6.0 (Othieno, 1992). Soil pH is influenced by many soil chemical parameters and may change seasonally depending on the external input used (Kamau, 2008).

Following the Brazil soil fertility classification from soil laboratories analyses result, (Raij, Cantarella, Quaggio, & Furlani, 1996), the soil P levels were high (0.0 to 0.1 m in BP_{1972}), medium (0.1 to 0.2 m in BP_{1972}), low (0.0 to 0.1 m in TH_{1987}) and very low (0.1 to 0.2 m in TH_{1987}). The K levels observed in the TH_{1987} site were considered medium, resulting in a relative yield between 91 and 100%, but the BP site K levels were considered high, providing on an output over 100%. The values of V soil obtained for both farms were considered very low and can result in production below 70%. The Ca and Mg for both farms (BP_{1972} and TH_{1987}) showed a low level, which would provide a relative yield of 71-90% and very high acidity resulting in a relative yield below 70%.

Areas cultivated with tea old (BP_{1972}) had higher values of soil exchangeable base cations than young tea (TH_{1987}). Wang *et al.* (2010) observed the opposite in his work, because after some years of cultivation of tea plants, the amount of soil exchangeable base cations decreased. Continuous cropping rapidly exhausts the soil of its mineral supply, thus reducing plant growth and hence profitable yields. Also a possible imbalance in the relative supply of nutrients by the soil may disrupt the growth rate of the tea plant (Kamau, 2008). This study did not observed the reported reducing fertility with increasing tea plantation age as our data showed that the older tea plantation (BP_{1972}) had had better fertility than soils under tea younger (TH_{1987}) as earlier discussed.

The higher values for FI suggest that areas of the TH_{1987} plot are in a more advanced process of recovery and, or maintenance of soil structure in relation to the BP_{1972} plot, as flocculation can beused as an index of soil aggregation and, therefore, greater stability of the structure of the soil. The higher values of WDC in the BP_{1972} plot indicate that this management predisposes the soil to more compaction due to a larger arrangement of the soil mass. Despite the high values of bulk density, it can be inferred that the soil of the TH_{1987} plot, structurally speaking, is less compressed than the BP_{1972} plot. High BD had been observed to affect grain yield. Czyż (2004) found grain yield of spring barley (*Hordeum vulgare*) in the field experiment were reduced significantly with increasing BD.

Porosity values reflect soil aggregation. The TH_{1987} plot soil had higher total porosity compared with the BP_{1972} plot, indictaing better soil structure, which can result in more rapid infiltration of rainwater, higher storage, less runoff and less susceptibility to erosion. Furthermore, soil aeration is an important component of soil physical quality as it influences the development of plant root systems, growth and yield of crops (Letey, Stolzy, Valoras, & Szuszkiewicz, 1962; Gerik, Morrison, & Chichester, 1987; Glinski & Lipiec, 1990; Czyż & Tomaszewska, 1993; Boone & Veen, 1994; Carter, White, & Ivany, 1994; Stepniewski, Gliński, & Ball, 1994; Czyż & Kukier, 1997; Czyż, Tomaszewska, & Dexter, 2001). However, it is very dynamic and varies significantly with a range of factors especially water content and BD (Czyż, 2004). High values of soil water content restrict soil aeration too and facilitate degradation of soil structure by compaction. Restricted aeration impairs plant growth by several mechanisms and ultimately reduces crop yields (Glinski & Stepniewski, 1985).

The TH_{1987} plot soil had lower PR compared to the BP_{1972} plot soil, thus showing a lower compression of these soils. The values of soil PR, in general, are low, considering the reference to 2000 kPa that could restrict root growth for most crops (Taylor, Roberson, & Jr. Parker, 1966; Lipeic & Hatano, 2003). These values certainly can be associated with high consistency of the soil, since these assessments were made during the rainy season, concurrent with the harvest. Drewry, Paton, & Monaghan (2004) submitted that soil compaction due to treading probably occurs in rainy season when soil is wet, and the soil physical condition improves during drying season.

The range of 30 to 50 g kg^{-1} of organic carbon is described by Craul (1999) as "good" for the establishment and maintenance of plants, resulting in a good resistance to soil compaction. Shukla, Lal, and Ebinger (2006) also considers the OM as a good indicator of quality in the soil, since OM promotes better soil aggregation, resulting in higher TP, besides retaining a higher amount of water in the soil. On the other hand, Pieri (1992) considers that OM or soil organic carbon alone is not indicative of maintaining the structure and suggests that levels of organic matter or organic carbon necessary to maintain good soil structure are related to the silt and clay content of soil (Pieri, 1992; Reynolds *et al.*, 2007). Analysis of the OM content for the 2 sites indicates similarity in values, however when the stability index (SI) of the soil structure at both sites was computed and compared, it was observed that the soils of the plots behaved differently. The BP plot would require higher OM content to maintain good soil structure. It is worth mentioning that both plots had SI values less than 5%, which indicates a degraded structure due to extensive loss of OM (Pieri, 1992),. The samples collected in the sub surface layers showed lower values of FI, which could be related to the lower levels of OM (Dutta *et al.*, 2010).

The two water retention curves showed different behavior between them, suggesting that age influenced the plantations studied here, since both site had similar management. In his work, Silva, Mafra, Albuquerque, Bayer, and Mielniczuk (2005) also found differences in water retention curves and concluded that the variations observed between the curves can be related to the influence of the structure and composition of materials in terms of OM and clay. This indicates that the soil water retention curve can be used as physical-hydric soil indicators. Soil in BP_{1972} plot due to WDC values may be more susceptible to compression which may reduce pore space and limit the movement of air and water through the soil. The combination of these two assumptions can lead to with drawal (by runoff and, or percolation) of the bases and other nutrients that may be adsorbed by colloids of this soil and may strongly affect the yield.

The higher values of soil resistance to penetration and the lower available water capacity among others in this study indicate that the root system of the tea grown in the BP_{1972} plot is probably being affected more when compared to the TH_{1987} plot, resulting in a lower root penetration and access to water and nutrients, resulting in a significant drop in productivity of tea. PR is regarded as a useful measure of soil impedance to root growth (Bengough & Mullins, 1990). A common response of root system to increasing compaction level is decreased root size, retarded root penetration and smaller rooting depth (Glinski & Lipiec 1990). This is mostly due to excessive mechanical impedance and insufficient aeration depending on soil wetness (Lipiec & Hatano, 2003). This problem (higher values of soil resistance to penetration) in BP_{1972} is due to vehicular traffic accumulated (BP_{1972} have 15 years more cultivation than TH_{1987}). Lipiec & Hatano (2003) explain that the vast majority of soil compaction and shearing in modern agriculture is due to vehicular traffic, which is an integral part of the soil management system. So, these alterations in soil structure due to compaction influence many aspects of the soil such as strength, gas, water and heat, which in turn affect root and shoot growth and consequently crop production and environmental quality (Lipiec & Hatano, 2003).

Therefore, the changes in soil structure is as a result of the absence of techniques to pulverise the soil structure during the cultivation of tea and the stress distribution over time due to continuous traffic, during phytosanitary control, pruning and harvesting, the latter being responsible for the entry activity of the combine more than 20 times in the same location during a crop year. It should be noted that the harvest in teas the southern state of Sao Paulo, Brazil, occurs in the period from August to June; a rainy period, during which the soil due to its low internal strength is very susceptible to compression (Dias Júnior & Pierce, 1995).

Soil fertility is manifested in soil porosity. Thus, the soil must have a set of chemical and physical characteristics favorable to the growth of roots and the development of the tea plant or any plant, to be satisfactory. The chemical fertility of the soil (nutrient availability) has to be associated with soil physical (porosity and structure). The best structure of the soil in tea young (TH_{1987}) makes the chemicals more available to the tea plant. In contrast, the soils of the older tea plantation, (BP_{1972}) had higher soil physical degradation, and will consequently making the chemical elements in the soil less available to plant. The root system of tea plants in BP_{1972}, will probably have difficulties in deepening and expansion, due to increased physical impediments.

Many factors influence the complex chemical, physical, and biological processes which govern soil quality and crop productivity (Hati, Swarup, Singh, Misra, & Ghosh, 2006). But, the results presented in this study showed that there has been soil structural degradation in the tea plantations in the Ribeira Valley region, Brazil as a result of continuous cropping, which affected the production level and quality. These adverse physical changes under continuous cropping, by Bridge & Bell (1994) have some major implications for crop production. Rainfall infiltration into the soil is reduced, thereby altering water use efficiency, which may be critical in dryland areas and in drought years or when rainfall distribution is uneven, and will also contribute to increased soil erosion during high intensity rainfall events. Water and nutrients avaialability to the plant in the root zone is also impeded. It is therefore necessary to note that just as land preparation prior to tea establishment is essential, good maintenance of the soil physical characteristics during its cultivation to avoid problems associated with soil compaction (Coomaraswamy, Anandavijayan, & Abeysekera, 1988) and soil erosion is equally essential (Illukpitiya *et al*., 2004).

5. Conclusions

Our results in this study showed that the degradation of soil structural quality with increasing age in tea plantation provide a better explanation for for the level of productivity and quality of harvested tea in the region of Ribeira Valley – Brazil. Soil in the younger tea plantation had better structural configuration evidenced in better physical properties such as low soil bulk density, higher porosity, lower soil resistance to penetration and higher water capacity, thereby providing a better environment for the tea plant root – soil interaction with a consequent effect on the quality of tea harvested, and higher productivity. However, it is noteworthy that the adoption of conservation practices such as controlled traffic, and joint operations, may reduce the effect of structural degradation of soil in these areas. The area with better soil chemical properties did not translate to higher productivity and better quality of tea harvested, due to the unfavorable soil physical properties which affect hydro-physcial responses with consequences on the soil-root environment in the tea plantions.

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